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CONCEPT DESIGN OF THE PAYLOAD HANDLING MANIPULATOR SYSTEM

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National Aeronautics and Space Administration

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Houston, Texas

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1.0 INTRODUCTION

NASA Task 504 was initiated in May 1974 to provide a concept design of the Orbiter Payload Handling System. This report summarizes the results of the effort expended in support of Task 504 and serves as the final report to close out this task. The task provides a proven concept design described herein and Remote Manipulator System (RMS) requirements and interface definition. Results of a JSC manipulator simulation that has supported this task will be included as an appendix to this report as soon as the data is available.

The following JSC organizations contributed to this document:

Avionics Systems Engineering Division
Control Systems Development Division
Crew Training and Procedures Division
Flight Control Division
Spacecraft Design Division
Tracking and Communications Development Division

The difference between the Task 504 RMS baseline and the Orbiter baseline are described in Section 3.0. The Task 504 baseline is summarized in the following paragraphs.

The manipulator is a 50-foot structure (described in Section 4.0) consisting of 12-inch diameter tubular upper and lower arms, wrist assembly and end effector. The primary manipulator is mounted on the payload bay port longeron and with six joints providing six degrees of freedom has the capability to reach within a hemisphere from its mounting point. The Orbiter can support a secondary manipulator mounted on the starboard longeron for special missions. The two manipulators can be operated sequentially. The weight for the second manipulator will be chargeable to the weight for payloads. Figure 1-1 shows a schematic of the RMS.

The manipulator joints (described in Section 4.4) are actuated and braked by electro-mechanical devices. Electro-mechanical devices are also used for supporting and deploying the manipulator (Section 8.0).

The manipulator can apply a maximum of 15 pounds of tip force when fully extended. The tip of the manipulator will be designed for a maximum deflection of 0.1 in/pound of tip force. The maximum tip speed of the manipulator will be 2 ft/sec unloaded and 0.2 ft/sec loaded with a payload. The manipulator will be designed to automatically exchange end effectors. The payload retention subsystems (Section 10.0) will provide active longeron and keel fittings for deployable payloads. Payload installation and deployment aids are proposed for handling large payloads (Section 9.0). The manipulator, retention devices and payload installation and deployment aids can be jettisoned if they interfere with closing the payload bay doors.

RMS SCHEMATIC

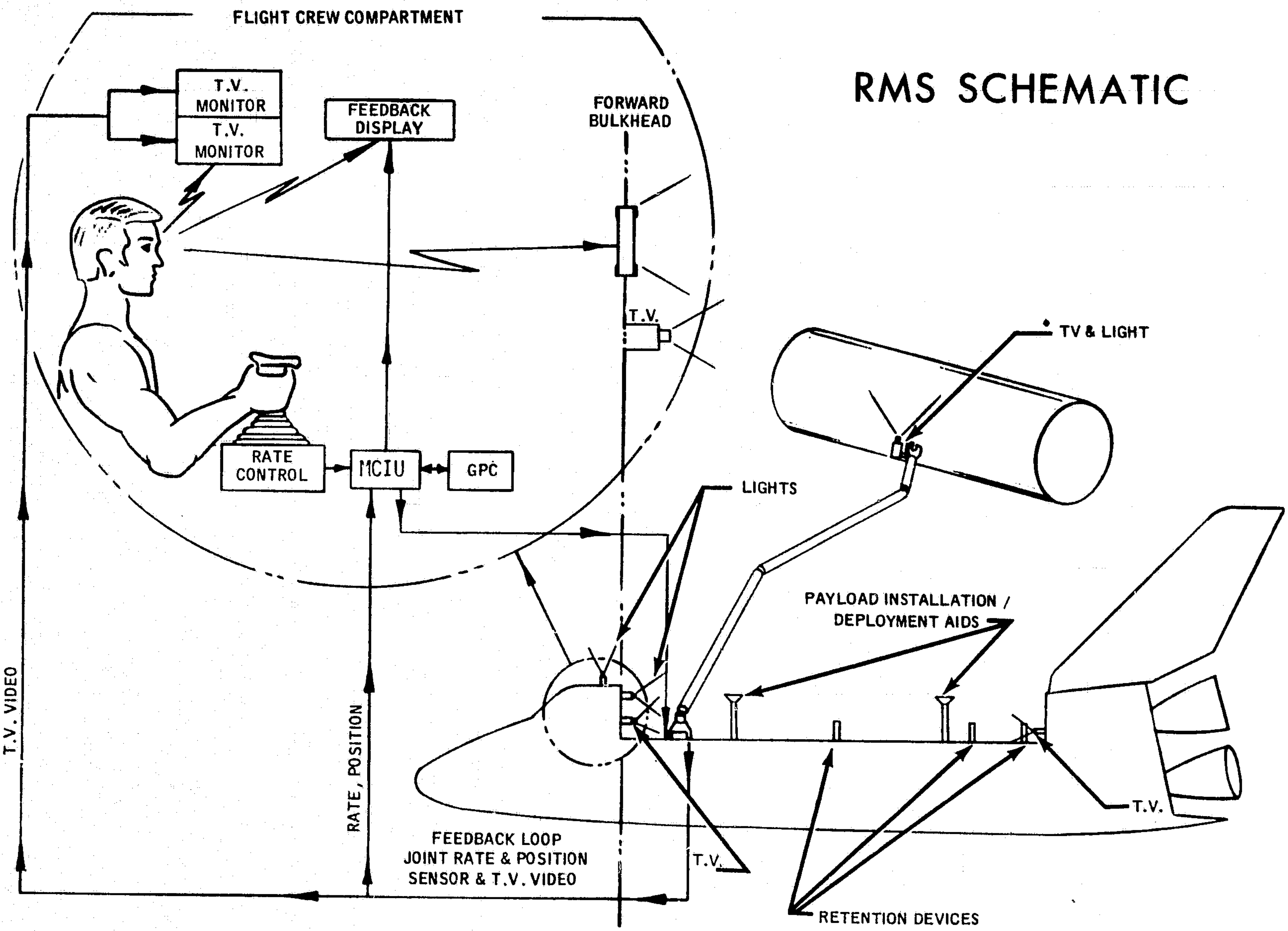

FIGURE 1-1

The RMS control system provides multi-mode control and programming for collision aviodance (Section 6.0).

Direct vision of payload operations is augmented by the closed-circuit television system (Section 14.0). A TV camera will be mounted on the manipulator wrist and two cameras will be mounted in the payload bay. All cameras will have remote control for pointing and zoom. Two monitors with split screen capability will be located at the RMS operator's station (Section 11.0).

Lighting will be provided to enhance direct and TV viewing (Section 13.0) with one light on the manipulator, one on the forward payload bay bulkhead, one on the top of the aft crew station for payload retrieval and six on the sides of the payload bay.

The crew station will be designed for standup operations with foot restraints. Rate controllers will be provided for manual manipulator control and appropriate status and monitoring displays (Section 12.0) provided as required for manipulator operation on two of three aft flight deck modular panels.

The RMS receives 28 volt DC electrical power from dual busses for actuation and pyro sequencing (Section 7.0).

The manipulator is designed for one-man operation as described in Section 16.0. Section 17.0 describes the approach to training for RMS operation.

The recommended control weight for the RMS is included in Section 18.0.

2.0 DESIGN REQUIREMENTS

2.1 RMS REQUIREMENTS

The following RMS requirements used in this study were established primarily from the Orbiter Vehicle End Item Specification for the Space Shuttle System, Specification No. MJ070-0001-1A, and JSC-07700 Volume X.

2.1.1 Basic Functions

The RMS shall be capable of performing the following operations with handling aids and retention devices installed on the Orbiter:

a. Remove the payloads shown on Figure 2-1 from the cargo bay and deploy the payloads to a stabilized condition.

b. Attach to the stabilized payloads shown on Figure 2-1 and move the payloads into position in the cargo bay for return to earth or for servicing of the payload.

The RMS of a rescue Orbiter shall also be capable of removing a crewman in a pressure garment from the area of the side access door or the airlock door of a disabled Orbiter and transferring the crewman to the area of the airlock of the rescue Orbiter.

The RMS shall perform other tasks that are incidental to the performance of the above functions.

2.1.2 Time Critical Payload Handling Requirements

The RMS shall be capable of deploying a 32,000-pound payload in seven minutes or less from release of payload tiedown to release of the payload to a stabilized condition external to the Orbiter cargo bay.

The RMS shall be capable of retrieving a stabilized payload of 25,000 pounds from the retrieval zone and stowing the payload in the cargo bay in seven minutes or less from initial grapple to payload tiedown.

2.1.3 Payload Positioning

The RMS shall be capable of deploying or retrieving and stowage of a 15-foot diameter by 60-foot long, 65,000-pound payload without exceeding a ± 3-inch clearance and a ± 3-inch end clearance in the cargo bay.

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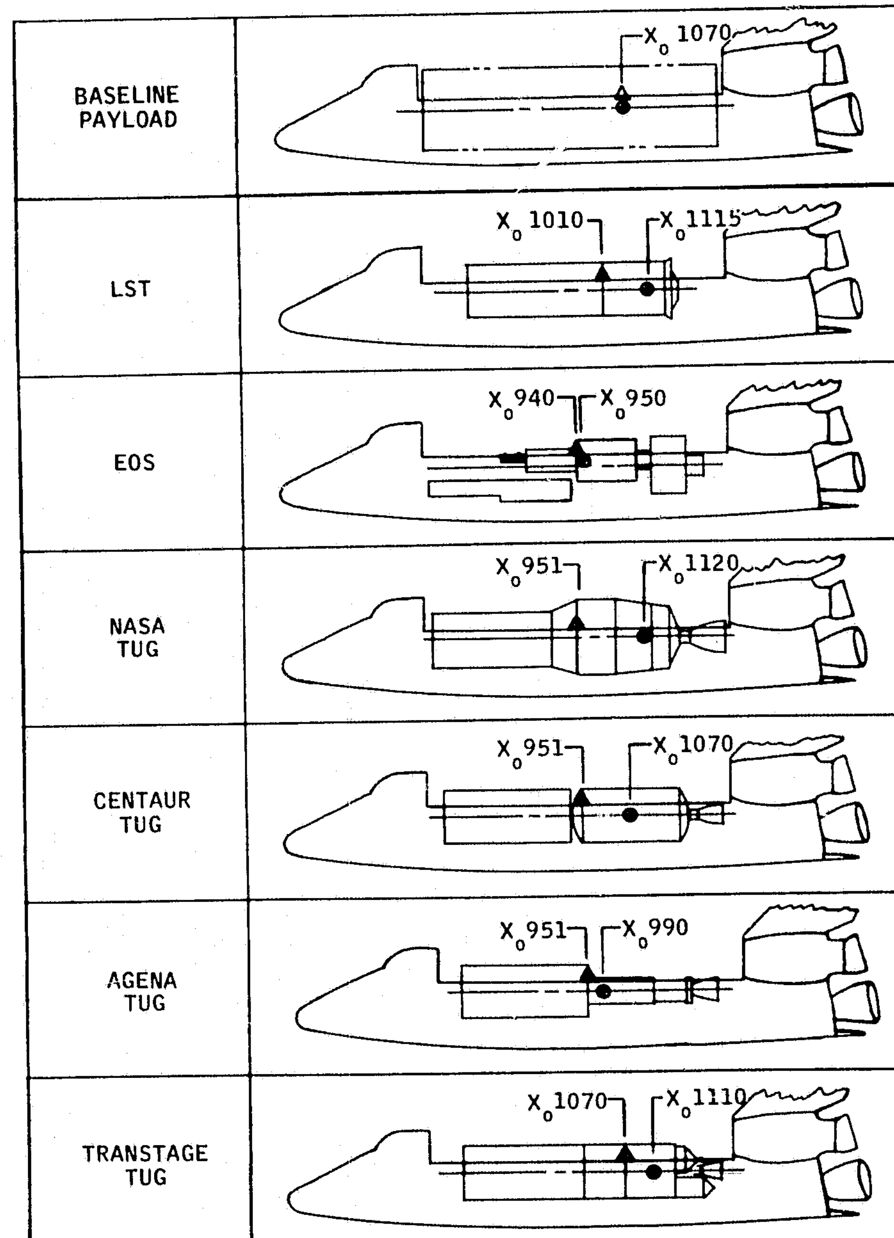
RMS

DESIGN PAYLOAD



● — C.G.
△ — GRAPPLE PT.

FIGURE 2-1

2.1.4 Payload Release

Release of the payload from the RMS shall result in the following maximum errors using the Orbiter's guidance and navigation inertial platform as a reference:

Attitude Error	-	15°
Linear Tip-off Motion	-	0.2 ft/sec
Angular Tip-off Motion	-	0.04°/sec

2.1.5 End Effector

A standard end effector will be provided for payload handling tasks; however, provisions shall be made in the RMS design to allow a change of end effectors in flight.

2.1.6 Arm Assembly Jettison

The arm assembly and retention latches shall be jettisonable without requiring EVA. The arm and/or retention latches shall not impact the Orbiter after jettison.

2.1.7 Mechanical Interface

All mechanical interfaces shall be nonfunctional in the performance of the RMS mission.

The manipulator arm must meet the Orbiter interface provided on the port longeron at station X_O 679.5 for the shoulder attachment, and at station X_O 911.05, 1153.5, and 1256.5 for the arm retention fittings.

The manipulator arm must be stowed in the 15-inch circle running from station X_O 673 to X_O 1305. The centerline of the 15-inch envelope is at station Z_O 446 and Y_O 89.5.

Prior to RMS operation, the manipulator arm, retention fittings, and shoulder deployment mechanism shall be capable of rotating outboard to allow a 15-foot by 60-foot payload to move vertically out of the cargo bay.

The second RMS arm shall meet the same interface requirements on the starboard longeron.

2.1.8 Reliability and Safety Requirements

In the event of a single failure, the RMS will fail operational. Degraded operation is acceptable. Automatic reconfiguration is highly desirable. No two failures within the RMS will result in an unsafe Orbiter condition.

In the event of a failure of the RMS that precludes stowage of the manipulator arm and subsequent closing of the cargo bay doors, the arm and retention devices may be jettisoned to allow cargo bay door closure.

2.1.9 RMS Maintenance Concept

Inflight maintenance shall not be a design requirement for the RMS. The RMS subsystems shall be designed for field maintenance as follows:

a. For electrical and/or electronic equipment (either installed or on the bench), checkout and replacement shall be at the integral package (black box) level. A "black box" is defined as a combination of factory replaceable units contained within a physical package, which is removable from the RMS as an integral unit.

b. For non-electrical and/or electronic equipment (either installed or on the bench), checkout and replacement shall be at the lowest replaceable serialized unit level, which includes only parts that are removable as integral units from the RMS.

2.1.10 Test Points

As applicable test points and test ports shall be provided and identified to permit rapid fault isolation to the replacement assembly or component.

2.1.11 Ground Support Equipment (GSE)

Maintenance of GSE shall be performed as specified in the GSE System Specification to be determined (TBD).

2.1.12 Useful Life

The RMS subsystems equipment and GSE shall be designed for an operating life and shelf life consistent with the operational and reliability requirements. Storage of explosive materials is covered in the explosive device subsystem.

2.2 INTERFACE REQUIREMENTS

For the RMS to achieve the previously listed requirements, the following Orbiter and payload capabilities are required:

2.2.1 Payload Stabilization

The payload must maintain the following conditions while the RMS is attempting to grapple:

a. Attitude rates ± 0.1 deg/sec.

b. Attitude hold which results in a ± 3 inch or less motion of the grapple fixture.

2.2.2 Payload-to-Payload Cradle Interface

Payloads that require a cradle in the cargo bay and attach and detach from the cradle for deployment or retrieval must be designed so the payload/cradle interface meets the same requirements as the payload bay/cargo interface.

2.2.3 Orbiter Stationkeeping

During RMS operation, the Orbiter shall maintain stationkeeping with attitude rate not to exceed ± 0.01 deg/sec. Range is TBD.

2.2.4 Interchangeability

The RMS may be removed if not required for a particular mission.

3.0 ORBITER BASELINE CONFIGURATION

The Orbiter baseline configuration for the RMS is described in Section 8.0 of JSC-07700, Volume XIV and is basically the same as the configuration described in Section 4.0 of this document except for the following differences:

a. The baseline joint torques are lower than those specified in Section 4.0.

b. The baseline RMS provides the capability to extend the wrist 24 inches, which is not recommended by this study.

c. The baseline angular travel of the shoulder pitch degree of freedom is 210°. This study has found 145° to be adequate. The baseline requirement for elbow pitch angular travel is 275°, but this study recommends 160°. The baseline requirement for wrist yaw angular travel is 200°, but for this study 240° has been selected.

d. The baseline control weight is currently 902 pounds whereas Task 504 has found that the weight should be 1273 pounds as shown in Section 18.0. Of the difference of 371 pounds, 205 pounds has been added in the weight for the Payload Installation and Deployment Aids, 100 pounds has been added in the weight for the manipulator arm and 66 pounds has been added for margin.

4.0 MANIPULATOR

4.1 DESIGN

The design of a manipulator which would satisfy the requirements of Section 2.0 required the integration of many elements. It was determined that six degrees of freedom would allow the manipulator to satisfy the basic requirements. Additional degrees of freedom were examined such as elbow roll and linear end effector extension. Elbow roll did not enhance the implementation of the outlined requirements, and the control system can provide straight line motion of the tip. Therefore, six degrees of freedom are necessary and additional degrees of freedom greatly increased design complexity and weight.

Early in the study, hydraulic powered joints were considered, but to be weight competitive with the electromechanical joint, assuming equal stiffness, some control intelligence would be required. Since a control technique of this type is not developed and since a hydraulic system provides greater potential contaimination in the payload bay, an electro-mechanical joint was baselined.

Consideration of manipulator dynamics (rigid body) found that joint torques, tip speed and tip stopping distance requirements of the manipulator with a specified payload attached contribute significantly to the manipulator weight, and subjectively, to its operation. Similarly, it was found that the manipulator stiffness requirement has a strong influence on weight and logically would have a critical effect on the control system (flexible-body dynamics).

In developing the requirements for torque, speed and stopping distance, it was found that a 0.2 ft/sec maximum tip speed is adequate in meeting the time-critical requirements in Section 2.0 for stowing a payload into the cargo bay from the fully-extended arm position. Two feet were judged to be adequate for tip stopping distance when moving a 32,000-pound payload (design case) at the maximum rated speed of 0.2 ft/sec. These two parameters then allow the joint torques to be analytically determined. With these performance parameters, it was determined that the 32,000-pound design payload could be translated 50 feet in approximately 290 seconds. Assuming rotational commands on a payload could be executed simultaneously with the above translation, approximately 130 seconds of time would be available for tracking, capture and stowage of the arm.

Manipulator stiffness is defined as the ratio of tip deflection to tip force for a fully-extended arm. The primary consideration in developing this requirement is to ensure a natural frequency for the arm which is compatible with the control system such that a controllable manipulator results. It has been found in years past through other studies that an arm stiffness of approximately 0.1 in/lb is sufficient. For purposes of this study and report, this value has been accepted without qualification. In addition to the control aspects, this stiffness results in reasonable tip deflections during acceleration and deceleration periods.

4.2 CONFIGURATION

As stated before, the manipulator is a six degree-of-freedom system of joints and rigid structural links with an overall length of 50 feet from the first joint to the tip when completely straightened. The arrangement and nomenclature of the joints and structural links are shown on Figure 4-1. The joint arrangement results in a gimbal order of shoulder yaw, shoulder pitch, elbow pitch, wrist pitch, wrist yaw and wrist roll. A terminal device is attached to the wrist for purposes of applying desired loads and/or motions and is called the end effector. The end effector has an additional degree of freedom, considered passive, for attaching and unattaching to payloads.

The manipulator geometry shown on Figure 4-2 has a primary location on the Orbiter minus "Y" longeron at X-station 679.5. As shown, the length from the shoulder pitch joint to the elbow pitch joint and from the elbow pitch joint to the wrist pitch joint is 264.5 inches each. Seventy-one inches is the specified dimension from the wrist pitch joint to the tip of the end effector. A nominal spacing of 18 inches should exist between the wrist pitch and yaw joints.

The joint angular travels are considered the minimum values (nominal) to satisfy the established requirements which include reaching all the payloads in the design payload model. Rationale used for determining these limits of travel are as follows:

4.2.1 Shoulder Yaw

The reasons for selecting 360° for this joint are to provide the maximum usable angle and allow the manipulator to be relocatable to the plus "Y" longeron without a special purpose shoulder assembly.

4.2.2 Shoulder Pitch

The 0° extreme is necessary for placing the manipulator in the stowed position. There is no requirement that makes it necessary to go beyond this limit. The other extreme of -145° is based primarily on preventing upper arm impact into the Orbiter forward bulkhead structure.

4.2.3 Elbow Pitch

The 160° extreme is based on compromising the needs for a maximum reach envelope into the cargo bay and minimizing the amount of "overlay" at the elbow joint with the lower arm folded back. The 0° extreme is necessary for the manipulator to be stowed along the longeron.

MANIPULATOR NOMENCLATURE SCHEMATIC

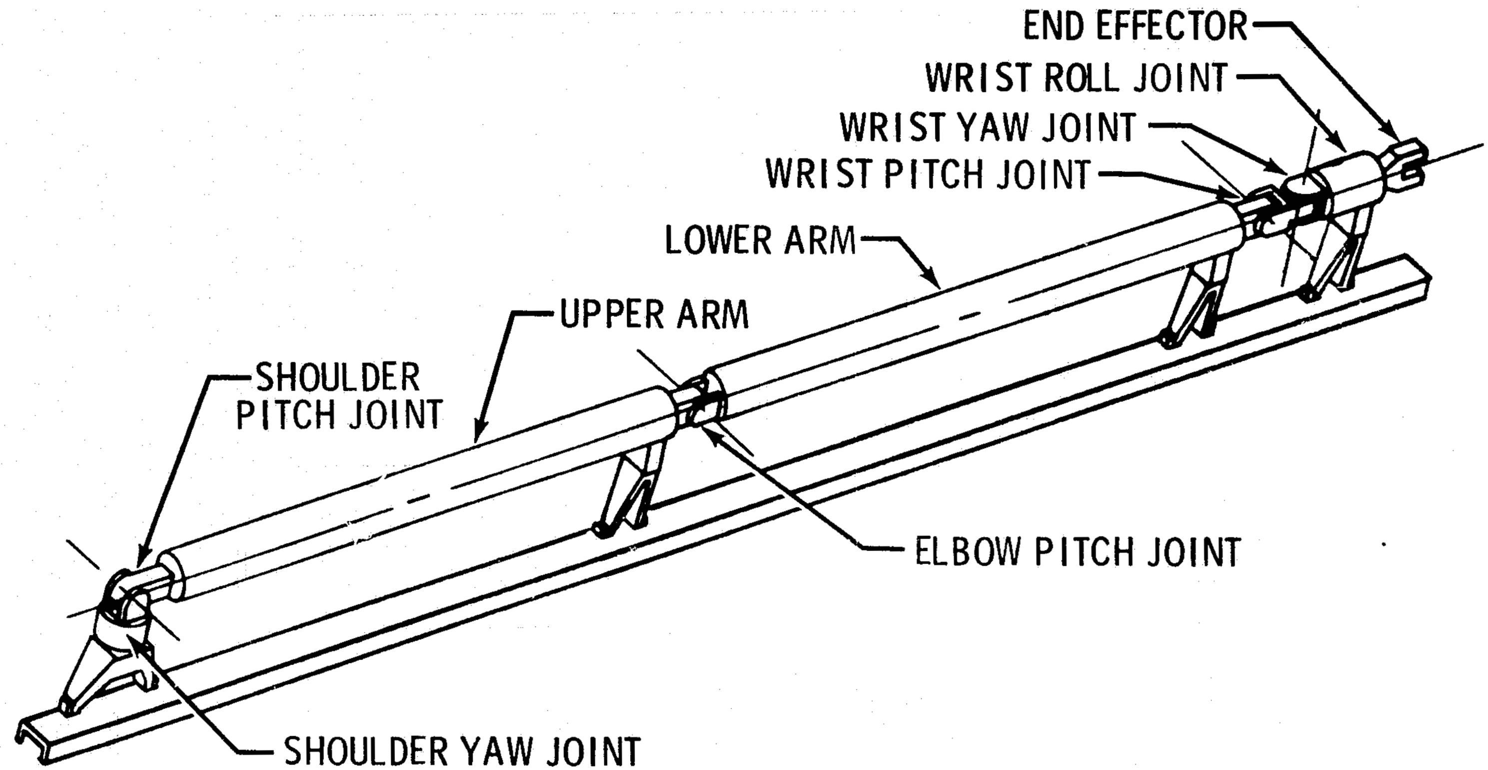


FIGURE 4-1

TASK NO. 504
MANIPULATOR BASELINE CONFIGURATION

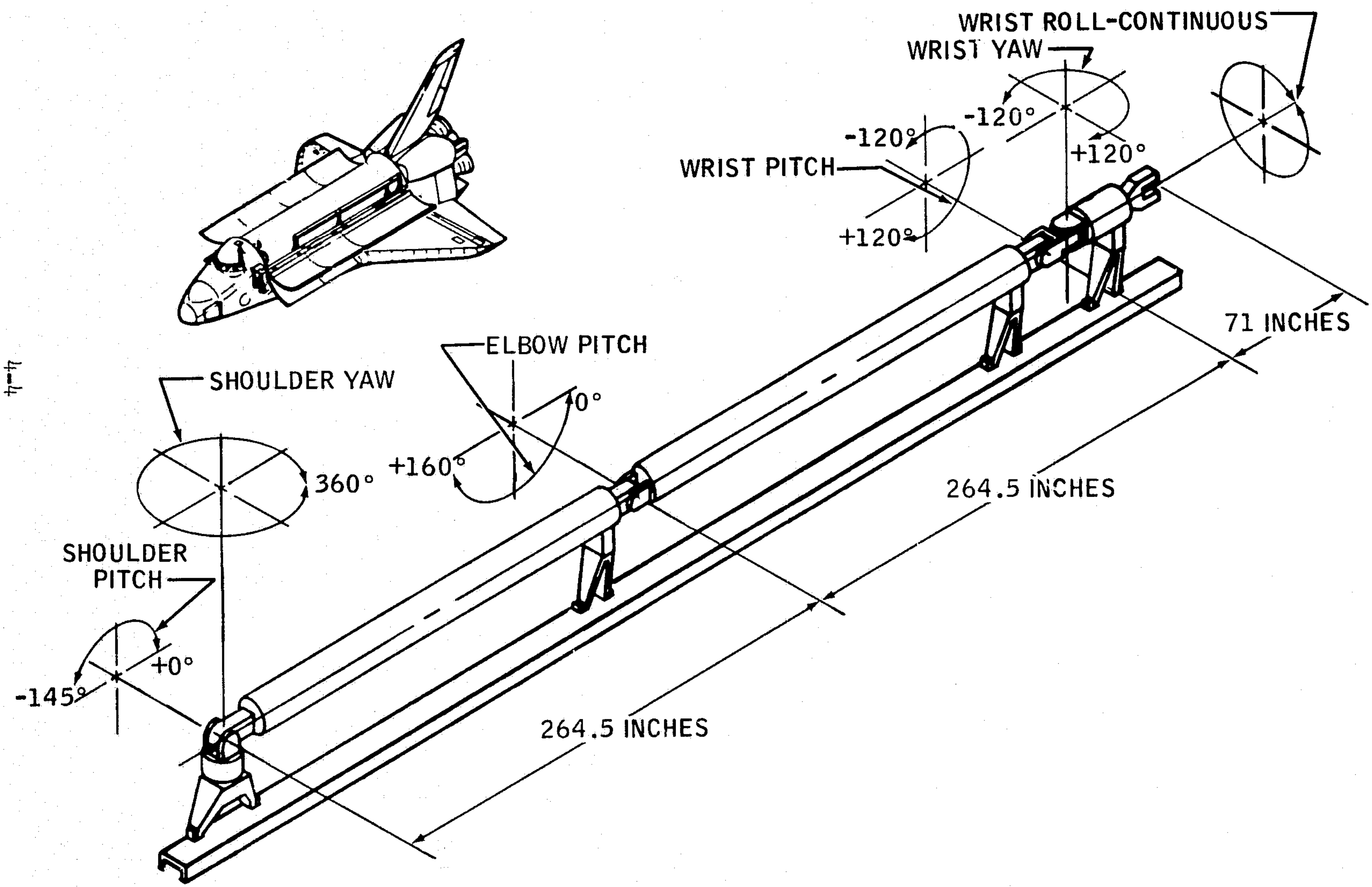


FIGURE 4-2

4.2.4 Wrist Pitch and Yaw

These angles were designed to be the maximum that the design will permit to allow versatility of the wrist.

4.2.5 Wrist Roll

The continuous angular travel for wrist roll is also for maximum versatility.

4.3 JOINT TORQUES AND RATES

In determining the torques and joint rates required to move a 32,000-pound payload at a velocity of 0.2 fps and to stop that payload in 2 feet, the following assumptions were made:

a. Rigid-body dynamics.

b. Single joint motion.

c. Specified requirements of 0.2 fps loaded velocity, 2.0 fps unloaded velocity and 2 ft stop distance (loaded) applies to the tip of a fully extended manipulator.

d. The baseline 32,000-pound payload is 60 feet long, 15 feet in diameter and is a homogeneous body.

e. Payload grappling fixture is located on the circumference at midlength.

f. Orbiter is inertially fixed.

Other assumptions or requirements used in an analysis are noted at the time of their use.

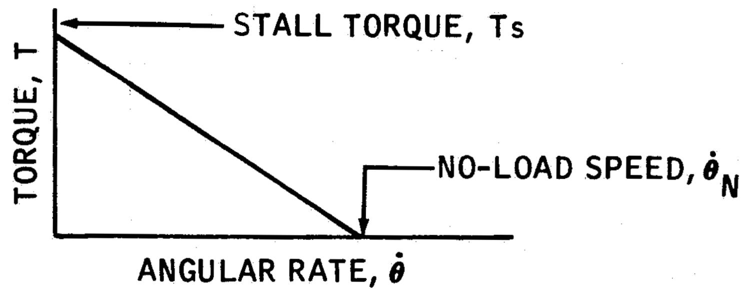
Determining the manipulator torque required to accelerate a moving payload is an easy problem when the acceleration is constant; however, in the case of a DC torque motor where the torque varies with speed and acceleration is not constant, the problem of determining the joint performance parameters becomes more complex. For purposes of this analysis, the joint performance for acceleration and deceleration are considered to be equal; i.e., time and distance to accelerate from rest to full speed is equal to time and distance to decelerate to a stop from full speed. The following paragraphs will describe the procedures and analyses necessary to obtain the data presented on Table 4-I.

TABLE 4-I,

MANIPULATOR JOINT PERFORMANCE PARAMETERS

	SHOULDER YAW	SHOULDER PITCH	ELBOW PITCH	WRIST PITCH	WRIST YAW	WRIST ROLL
TORQUE, STALL FT-LBS	772	772	502	231	213	213
JOINT RATE, MAX RAD/SEC (DEG/SEC)	.04 (2.29)	.04 (2.29)	.057 (3.27)	.083 (4.76)	.096 (5.50)	110 (6.30)
32,000 LB PAYLOAD (DESIGN CASE)						
JOINT RATE, RAD/SEC (DEG/SEC)	.004 (.229)	.004 (.229)	.0057 (.327)	.0083 (.476)	.0096 (.550)	.011 (.630)
TIP SPEED FT/SEC	.20	.20	.159	.049	.042	.63 DEG/SEC
STOP DISTANCE OF TIP FT	2.0	2.0	1.528	.464	354	5.47 DEG
STOP DISTANCE OF PAYLOAD EXTREMITY, FT	2.864	2.864	2.864	2.864	2.864	2.864
ACCELERATION TIME TO FULL SPEED, SEC	19.64	19.64	18.70	18.61	18.63	15.71

A DC torque motor has an ideal torque-speed curve as follows:



The torque equation for the above curve is:

$$T = T_s - \frac{\dot{\Theta}}{\dot{\Theta}_n} T_s \qquad \text{(Eq. 4-1)}$$

Realizing that motor torque can be expressed in terms of motor acceleration and inertial loading ($T=I\ddot{\Theta}$), eq. 4-1 can be rearranged into a differential equation as follows:

$$\ddot{\Theta} + \frac{T_s}{I\dot{\Theta}_n}\dot{\Theta} - \frac{T_s}{I} = 0 \qquad \text{(Eq. 4-2)}$$

Using the initial conditions (time=0) that $\Theta=\dot{\Theta}=0$ and $\ddot{\Theta} = \frac{T_s}{I}$, the following solutions for angular displacement, angular velocity and angular acceleration respectively, can be obtained.

$$\Theta = \frac{I\dot{\Theta}_n^{\,2}}{T_s} \exp \frac{-T_s}{I\dot{\Theta}_n} t + \dot{\Theta}_n t - \frac{I\dot{\Theta}_n^{\,2}}{T_s} \qquad \text{(Eq. 4-3)}$$

$$\dot{\Theta} = -\dot{\Theta}_n \exp \frac{-T_s}{I\dot{\Theta}_n} t + \dot{\Theta}_n \qquad \text{(Eq. 4-4)}$$

$$\ddot{\Theta} = \frac{T_s}{I} \exp \frac{-T_s}{I\dot{\Theta}_n} t \qquad \text{(Eq. 4-5)}$$

Simultaneously solving equations 4-3 and 4-4 by equating the time required to reach an angular displacement (stop distance, Θ_S) and an angular speed (full-load speed, $\dot{\Theta}_F$), the following expression for stall torque can be obtained:

$$T_s = - \frac{I\dot{\Theta}_n}{\Theta_s} \left[\dot{\Theta}_n \mathrm{Ln} \left(\frac{\dot{\Theta}_n - \dot{\Theta}_f}{\dot{\Theta}_n} \right) + \dot{\Theta}_f \right] \qquad \text{(Eq. 4-6)}$$

The shoulder joints are considered as the primary joints in meeting the requirements of tip speeds and stopping distances. They are, therefore, analyzed first and the remaining joint parameters then follow. Kinematic and geometric relationships are used to determine the joint rates and payload extremity stopping distance for the shoulder pitch and yaw joints. Stall torque can be calculated from equation 4-6 and acceleration time can be determined from either equations 4-3 or 4-4.

For the manipulator to maintain "dynamic equilibrium" in a given geometry, there must exist a definite relationship between the shoulder joint torque and the remaining joint torques. Referring to Figure 4-3, the following equation can be derived:

$$T_x \doteq T_{sh} \left[1 - \frac{m(\ell+R)x}{I_m + m(\ell+R)^2} \right] \qquad \text{(Eq. 4-7)}$$

Except for wrist roll, this equation can be used in calculating the required stall torque for each of the remaining joints.

The payload extremity stopping distance for each joint is required to equal that of the shoulder joint. Geometric relationships can be used to determine the corresponding joint stopping angles. Referring to equation 4-6, T_S and Θ_S are known for each joint and any relationship between $\dot{\Theta}_n$ and $\dot{\Theta}_f$ which satisfies that equation can be selected. Since $\dot{\Theta}_n$ for the shoulder joints was required to be 10 times $\dot{\Theta}_f$, this ratio was used for the remaining joints.

MANIPULATOR/PAYLOAD DYNAMIC EQUILIBRIUM DIAGRAM

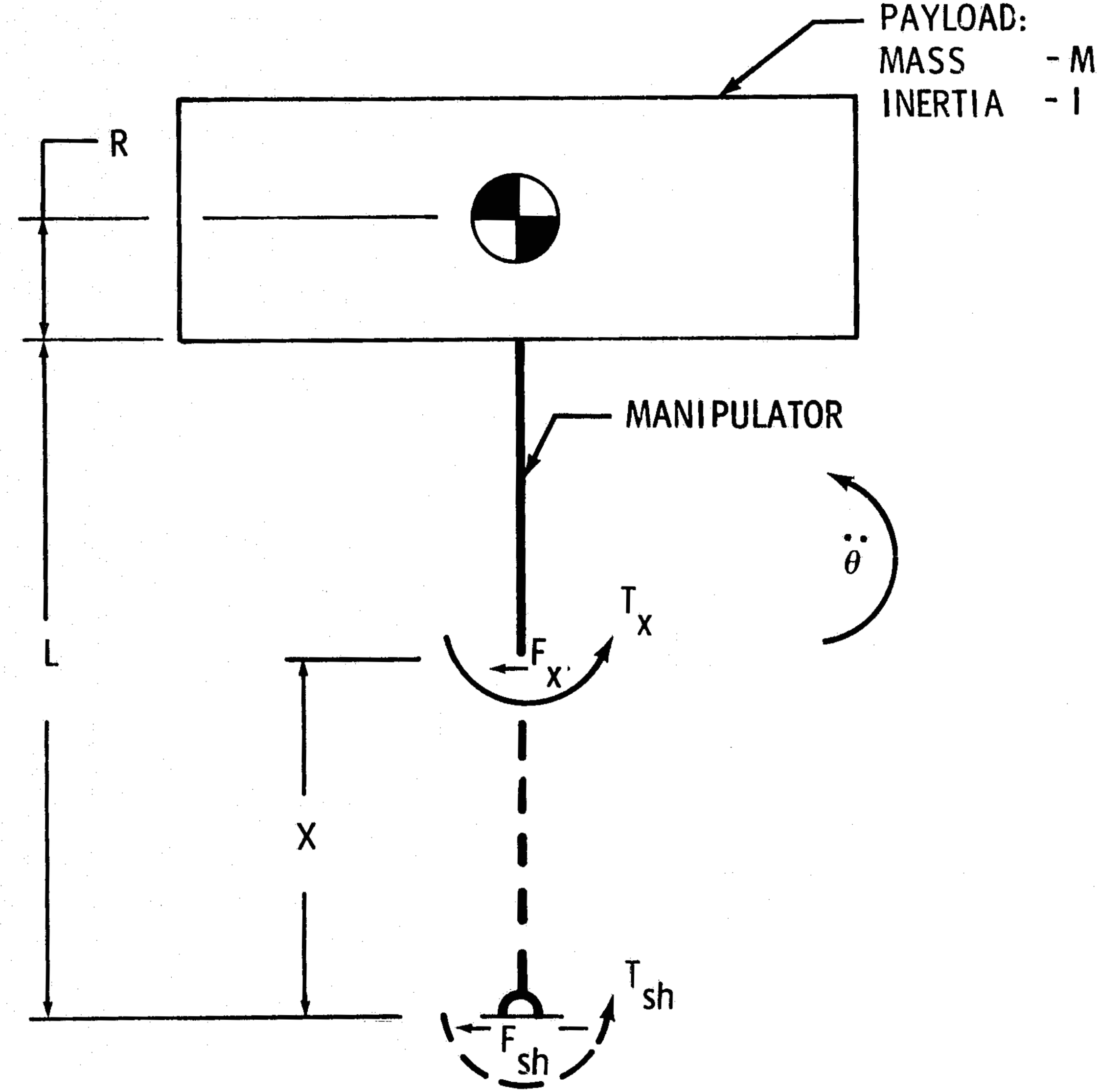


FIGURE 4-3

As noted, T_s cannot be calculated for the wrist roll joint by use of equation 4-7. This is because the roll axis is not aligned with either of the shoulder axes. If the wrist yaw joint is at 90°, the wrist roll axis then aligns itself with shoulder pitch and equation 4-7 applies. Additionally, if wrist pitch is at 90°, wrist roll is aligned with shoulder yaw and equation 4-7 applies. Similarly, other geometries can exist where wrist roll is aligned with a shoulder joint axis and equation 4-7 would apply. The applicable case is selected to be when wrist yaw is at 90° and wrist roll must have a torque equal to wrist yaw.

There are three assumptions noted in the beginning that require further discussion. The assumption of an inertially fixed Orbiter is invalid for those cases where RCS firing is prohibited. In such cases, the torques required to accomplish the required payload handling tasks are less. Since the torque ratings are those calculated for an inertially fixed Orbiter, the time and distance for start/stop operations with a "free" Orbiter will actually be less than those listed as requirements.

The remaining two assumptions which require further discussion concern the location of the grappling fixture and the payload being a homogeneous body. These assumptions, in effect, cause the payload c.g. to be in line with the manipulator arm. Since the actual payloads will, in all probability, have an offset c.g. with respect to the grappling fixture, it is necessary to examine this case and be aware of the consequences.

Considering the 32,000-pound design case payload and using the maximum c.g. offset of 14.08 feet as shown on Figure 2-1, RMS Design Payload, an analysis was performed wherein rigid body dynamics and single shoulder joint motion was used. The intent of the analysis was to determine the amount of over-torque the elbow and wrist joints were subjected to when the shoulder joint was commanded to full rated torque. At time = 0, the shoulder is at rated stall torque and the elbow joint, wrist pitch joint and wrist yaw joint are approximately 2.8%, 12.6% and 13.6% over rated stall torque, respectively. After six seconds, the shoulder torque has decreased such that the elbow torque is equal to or less than its maximum rated torque. After 18 seconds, the shoulder joint torque has decreased such that the wrist joints are at torques equal to or less than their maximum rated values. These over-torques can be handled one of three ways: First, the joints can be allowed to backdrive; secondly, the joints can be designed to deliver over-torques for short periods of time; and third, the shoulder torque can be limited to values which prevent the over-torques from developing.

4.4 JOINT MECHANICAL DESIGN

The manipulator joint is comprised of two parts: the end fittings and the electro-mechanical drive unit.

The end fitting is a high efficiency structure. Each of the structure elements would be fabricated from a material with a high stiffness/weight ratio such as titanium. This structure should result in a minimum weight that will satisfy the stiffness requirements of Section 4.5. The design of the end fitting should allow the required angular travel of each joint. The end fitting must accept a 12-inch diameter boom on one end and the electro-mechanical actuator on the other.

The end fitting design will also incorporate cable clamps, straps, or mechanisms to retain and guide control and power cables during angular travel of the joints.

To provide minimum weight for the required torque and stiffness, a hinge type actuator is baselined. With the actuator and hinge combined, weight and volume are minimized. The joint design is basically a balanced multi-planetary drive with a two motor drive configuration and is schematically shown in Figure 4-4. A general arrangement of a hinge type actuator is shown in Figure 4-5.

The electro-mechanical joint consists of drive motors, gear reduction drive, hinge/housing assembly, tachometer generators, selective brake, and position indicators.

The drive motors should be 28 volt permanent magnet D.C. motors. There are several reasons for selecting this type motor. As shown previously, high torque and extremely low speeds are required for the manipulator joints. Direct current motors have the unique characteristics of high torque at low speed. Also, the D.C. motor lends itself to servo control since no power is used in the field structure and the stator magnetic flux remains constant at all levels of armature current. Therefore, the speed-torque curve of the permanent magnet motor is linear over the motors operating range. For a given air gap, the radial dimension of a permanent magnet motor is approximately one fourth that of a wound field motor.

The gear reduction drive proposed for all joints (with the possible exception of wrist roll) is a two-stage multi-planetary drive that acts as a hinge. An input shaft, driven by two motors, drives the first stage sun gear causing rotation of its planet gears. These planet gears drive the planet gears of the second stage resulting in relative motion of the ring gears which are part of the hinge/housing assembly. The concept for the multi-planetary gear drive for the shoulder pitch joint is shown in Figure 4-6 and associated gear design data is presented in Table 4-II.

MANIPULATOR JOINT SCHEMATIC

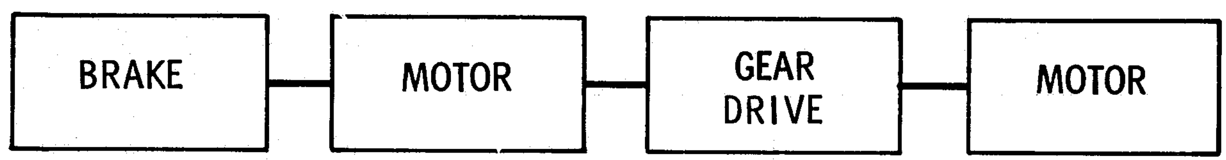


FIGURE 4-4

HINGE TYPE ACTUATOR

1. FIXED RINGS
2. SUPPORT RING
3. SUN GEAR
4. INPUT SHAFT
5. OUTPUT RING
6. SPINDLE

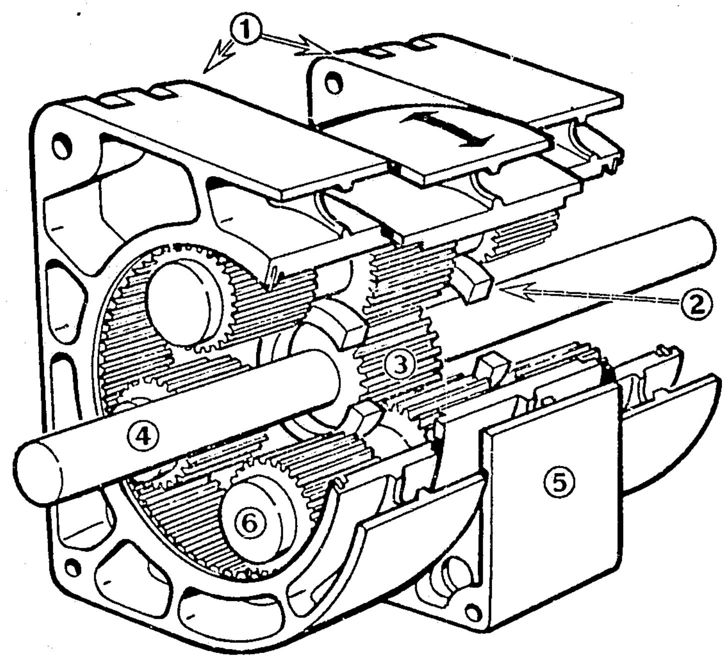
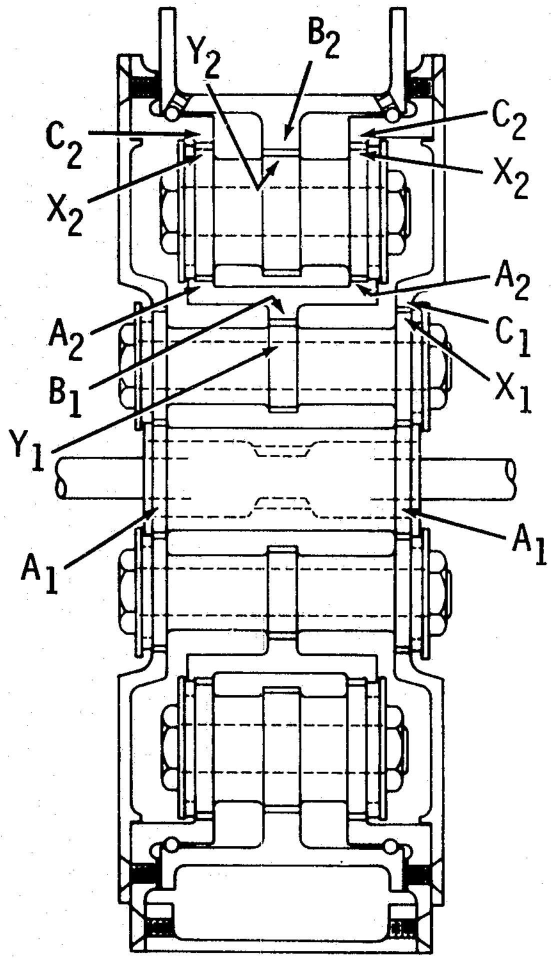


FIGURE 4-5

MANIPULATOR SHOULDER PITCH JOINT HINGE ACTUATOR



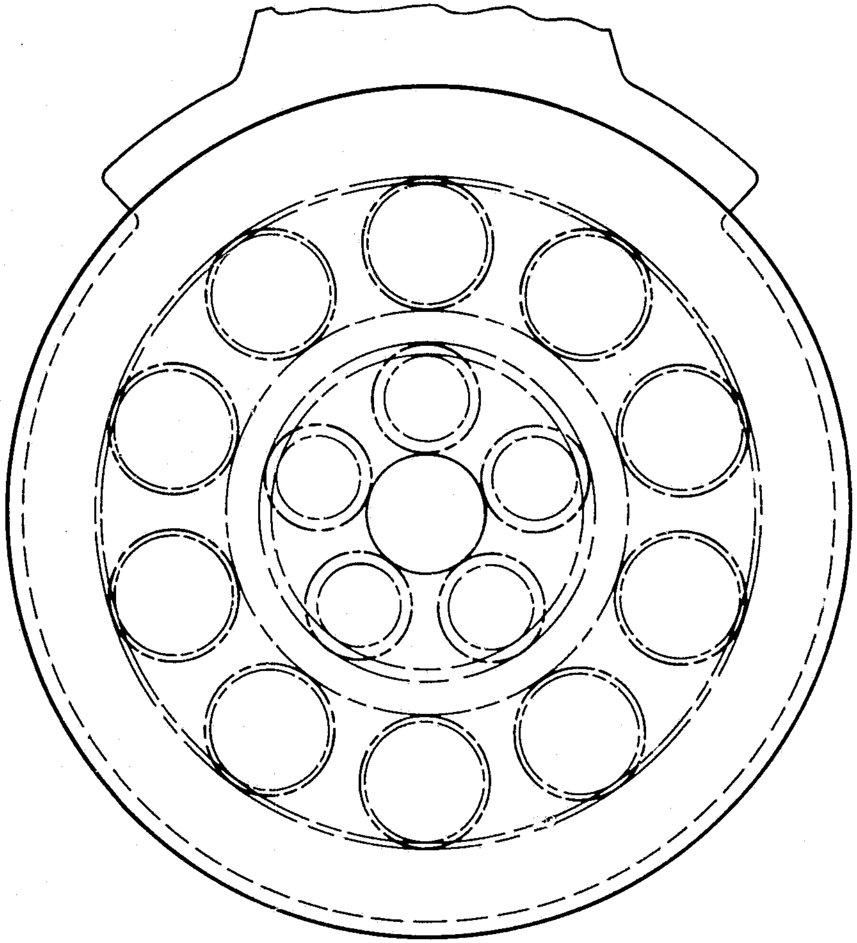


FIGURE 4-6

TABLE 4-II

DESIGN DATA FOR MANIPULATOR SHOULDER PITCH JOINT HINGE ACTUATOR

OUTPUT DIFFERENTIAL - 10 PLANETS					
NAME	NO.	TEETH	DIAMETRAL PITCH	P.D.	FACE WIDTH
SUN GEAR	A_2	60	14	4.2857	.200 x 2
PLANET GEAR	X_2	20	14	1.42857	.200 x 2
RING GEAR	C_2	100	14	7.14285	.200 x 2
PLANET GEAR	Y_2	22	17.15	1.2828	.391
RING GEAR	B_2	120	17.15	6.9970	.391
FIRST PLANETARY - 5 PLANETS					
SUN GEAR	A_1	30	25	1.200	.156 x 2
PLANET GEAR	X_1	30	25	1.200	.156 x 2
RING GEAR	C_1	90	25	3.600	.156 x 2
PLANET GEAR	Y_1	25	27	.9230	.300
OUTPUT RING GEAR	B_1	90	27	3.3230	.300

The planet gears are separable which permits assembly of the gear drive. The planet gears are straight cut spur gears and have rollers attached to each end to react radial loads. Additionally, the rollers act as retainers for holding the planet gears in place. The hinge/housing assembly is comprised of a center ring gear, right ring gear, and left ring gear. The right ring gear and left ring gear are held to the center ring gear by balls which are inserted in the filling holes on the right and left ring gears. The balls serve two functions; first, to retain the left and right ring gears to the center ring gear and second, to provide a full complement bearing on each side of the hinge/housing assembly to support the loads imposed on the joint.

To provide joint rate information, two tachometer generators will be attached to the motor shaft. The tachometer generators are located on the motor shaft for maximum output since the angular rate is the greatest at this point. To determine joint position, two position sensors will be provided. A selective brake is provided to secure the joint during stowage and any other required lockout position. See Figure 4-7.

To analyze and design a manipulator joint, general design data for motor and gear drive should be available; however, this general data was not available so another approach was required. As stated, the torque-speed curve of the motor is assumed to be linear. To determine motor parameters, data on eight motors was obtained from a manufacturers catalog. These motors had an operating voltage of 28.4 $\pm$ 1.4 volts and limited to 155°C winding temperature. Using statistical analysis, the following data was obtained:

Back EMF, K_B, Volts/Rad/Sec	- $K_B = .56015 \text{ Ln } T_s + .499$
Voltage Limit, Volts	- 28.4 $\pm$ 1.4V
Motor Resistance, R_m, Ohms	- No Obvious Relationship
Motor Inductance, L_m, Millihenries	- No Obvious Relationship
Torque Sensitivity, K_T Ft lb/amp	- $K_T = .41914 \text{ Ln } T_s + .3612$ $K_T = .190\, W^{.8752}$ (155° winding)
Motor Weight, W lb	- $T_s = .3382\, W^{.8752}$

Based on this data, a weight estimate can be determined for the motor given a required torque.

TYPICAL MANIPULATOR JOINT DESIGN

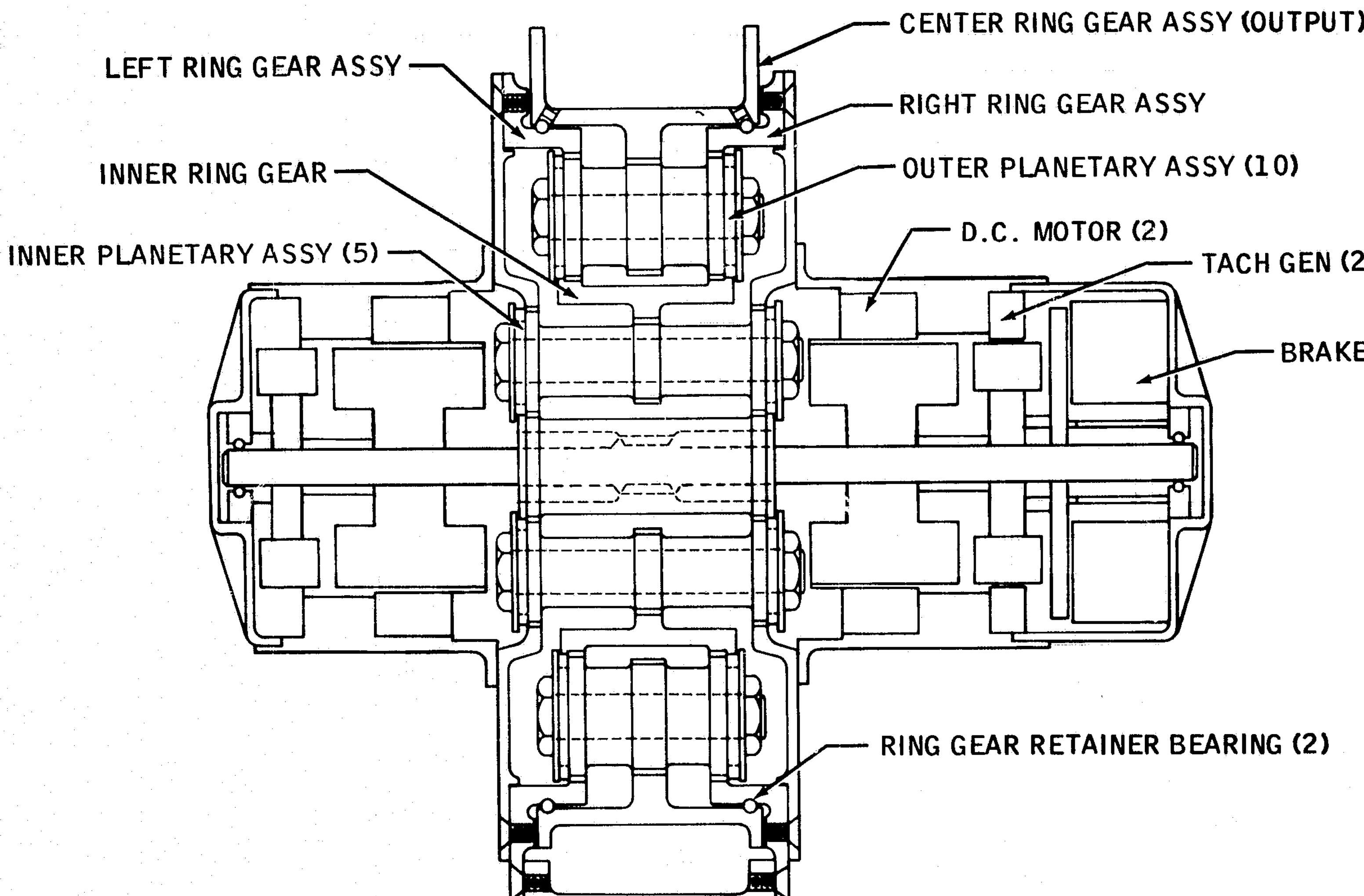


FIGURE 4-7

To determine joint drive parameters, a math model was developed. Since specific design data for multi-planetary hinge type actuators was not available, manufacturers data for existing hinge type actuators (Power Hinge) was used to determine gear drive equations. The Power Hinge used for analysis is limited to a gear ratio of 40 to 1. This limitation is based on gear drive efficiency and size.

The manufacturers data for the Power Hinge resulted in the following diameter, weight and stiffness relationships:

Outside Diameter, D_O Inches	- $D_O = .3255\ T_J^{.3322}$
Weight, W, lb.	- $W = 3.96 \times 10^{-3} T_J^{.9699}$
Stiffness, K_X, in lb/Rad	- $K_X = 3.544 \times 10^5\ W^{1.101}$

An added increment of weight must be added to the power hinge drive weight for the total gear drive weight if the ratio desired is greater than 40 to 1. Therefore, two weight relationships are required. One for the power hinge and one for the additional ratio. The latter is referred to as the intermediate drive.

To determine the gear ratio for a minimum weight, the relationship of weight to gear ratio for the intermediate drive is required. For analysis, the intermediate drive is in tandem with the power hinge. By varying the ratio of the intermediate drive, the overall ratio can be varied from 40:1 to the ratio desired.

By combining the equation for motor weight, power hinge weight, and intermediate drive weight, a weight relationship for the joint as a function of gear ratio is obtained.

Since the weight/stiffness relationship is known only for the 40:1 drive, an adjusted relationship must be derived for the total gear drive since a ratio other than 40:1 is desired. To obtain this relationship, it is assumed the intermediate drive is infinitely stiff and the unit weight will be added to the 40:1 ratio drive weight. The adjusted weight/stiffness equation will take the form of

$$W = C_1\ K_X^{\ C_2} + C_3$$

where the constants C_1 and C_2 are dependent on gear ratio. C_3 is the drive motor weight constant.

The weight-stiffness equations for the shoulder, elbow and wrist joints resulting from this analysis are as follows:

$$W_S = 2.3455 \times 10^{-5} K_S^{.872} + 31.4$$

$$W_E = 2.3455 \times 10^{-5} K_E^{.872} + 18.6$$

$$W_W = 2.3455 \times 10^{-5} K_W^{.872} + 12.3$$

The analytical results obtained above are expected to correlate well with the multi-planetary drive system proposed for the manipulator concept design. The proposed multi-planetary gear drive design has increased efficiency and performance over previously considered joint concepts. A complete analysis has been performed and shows the proposed design to have stiffness and weight characteristics suitable for this application.

4.5 JOINT/ARM STIFFNESS

The requirement to minimize weight and the need to have a relatively stiff system requires a rigorous analysis to establish how the overall stiffness is to be divided between the various joints and arms. The requirement for tip stiffness to be 0.1 in/lb is reasonable; however, it is considered to have a relatively large tolerance that permits a less than perfect analysis.

For the stiffness analysis, the manipulator is configured as shown on Figure 4-8 and the Orbiter structure and manipulator shoulder/deployment mechanism is considered rigid. The three joints have torsional stiffness in the axis of rotation, designated K_S, K_E and K_W for the shoulder, elbow and wrist joints, respectively. The structural segments have stiffness parameters, modulus of elasticity, E, and area moment of inertia, I, where E is the same for the upper and lower arms and I_u and I_l are for the upper arm and lower arm respectively. Each arm is uniform over its length. The wrist segment is arbitrarily assigned values of $E = 1(10)^7$ psi and $I = 50\ in^4$.

For a tip force perpendicular to the manipulator longitudinal axis and in the direction that causes joint rotation, an expression for the tip deflection per pound of tip force can be written in terms of the individual joint and arm stiffness parameters. Additionally, an expression for the joint weights in terms of joint stiffness parameters can be written using the relationships derived in Section 4.4 and arm weights can be expressed in terms of their area moments of inertia. Combining these two equations, weight can be expressed as a function of the joint stiffnesses, the upper arm inertia and the overall tip stiffness, K, in the general form:

$$WT = f(K_s, K_e, K_w, I_u, K)$$

To determine the minimum weight relationships between the above parameters (K is an input that would be a constant), partial derivatives of the expression with respect to each of the variables can be taken and set equal to zero. Four equations will result and a relationship between these four equations can be developed. Choosing a value for one unknown will allow solutions for the remaining three and a weight calculation can then be made. Choosing sufficiently different values for the initial unknown, one can obtain a spread of weight data from which the minimum weight can be selected along with the values of K_s, K_e, K_w, I_u and I_l.

With the above parameters determined, the shoulder yaw and pitch joints are assigned the value of K_s, elbow pitch joint is assigned K_e, and wrist pitch, yaw and roll joints are assigned the value at K_w. Upper and lower arm cross-section properties can be determined by use of the arm diameter and its arm moment of inertia resulting from the above analysis.

CONFIGURATION FOR MANIPULATOR JOINT/ARM STIFFNESS ANALYSIS

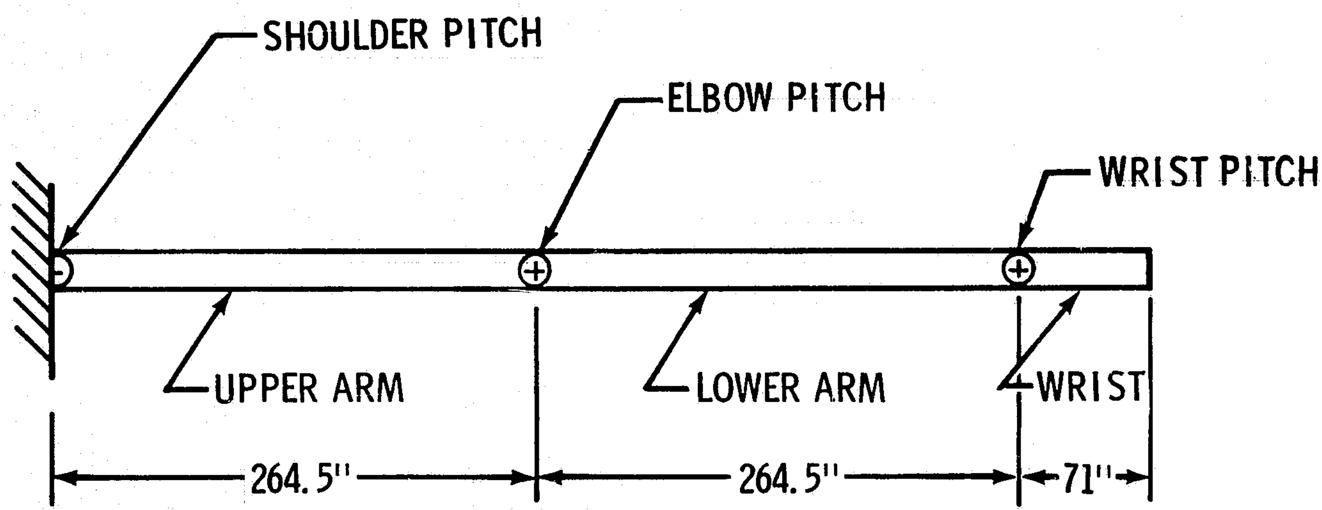


FIGURE 4-8

The input conditions for the manipulator stiffness calculations are:

Modulus of elasticity, E, for upper and lower arm, psi	- 25×10^6
Modulus of elasticity, E, for wrist segment, psi	- 10×10^6
Area moment of inertia, I, for wrist segment, in^4	- 50
Material density, upper and lower arms, lb/in^3	- .056
Material density, wrist segment, lb/in^3	- .10
Diameter, upper and lower arm, inches	- 12
Weight-stiffness equation, shoulder joint	- $W = 2.3455 \times (10)^{-5}(K_S)^{.872} + 31.4$
Weight-stiffness equation, elbow joint	- $W = 2.3455 \times (10)^{-5}(K_E)^{.872} + 18.6$
Weight-stiffness equation wrist joint	- $W = 2.3455 \times (10)^{-5}(K_W)^{.872} + 12.3$

Using these inputs in the analysis described above, the following arm and joint parameters are obtained:

<u>JOINT STIFFNESS, in-lb/rad</u>

Shoulder yaw	1.40×10^7
Shoulder pitch	1.40×10^7
Elbow pitch	7.53×10^6
Wrist pitch	1.43×10^6
Wrist yaw	1.43×10^6
Wrist roll	1.43×10^6

<u>ARM INERTIA, in^4</u>

Upper arm	62.33
Lower arm	28.55

4.6 ARM DESIGN

The upper and lower arms shall be fabricated from a high strength-to-weight material with stiffness being the key parameter in weight minimization studies. A baseline of graphite/epoxy composite was selected because of its stiffness-to weight characteristics.

For purposes of weight and stiffness calculations, 12.0 inches were assumed as the outside diameter for both arms. This dimension was used rather than the 15.0 inch maximum to allow space for protrusions up to 1.5 inches along the surfaces. Material properties assumed for all calculations were modulus of elasticity for bending deflection - 25×10^6 psi; density - .056 lbs/in^3.

The preliminary design of the arms resulted in wall thicknesses for the upper and lower arms of 0.092 in. and 0.042 in., respectively. The exact derivation of these numbers is presented in more detail in Section 4.5.

5.0 END EFFECTOR

5.1 END EFFECTOR REQUIREMENTS

The end effector is required to perform the mechanical coupling between the manipulator arm and payload. It attaches to the manipulator wrist-roll motor and physically interfaces with the payload grappling fixture. This grappling fixture forms an integral part of the end effector design.

The end effector is required to attach to the grappling fixture with an initial linear misalignment of ±4 inches, x, y, and z, and an angular misalignment of ±15 degrees, pitch, yaw and roll. The interface after coupling is required to react a minimum of 1.5 times the maximum load which the RMS can induce at that point. The structural deflection of the end effector/grappling fixture, when subjected to this maximum load, shall not exceed 0.15 degrees in pitch, yaw, and roll, and 0.1 inches x, y, and z.

The design of the end effector and grappling fixture shall be such that the end effector when in position for capturing the grappling fixture, does not obscure the operators vision of the target area. The lack of precise definitions of viewing angles, camera positions, viewing aids, et cetera, compell the end effector/grapple fixture design to entail unobscured alignment, both linear and angular, of the x, y, and z axes. Should the end effector fail to be within the designed misalignment tolerances or if, for some reason fails to acquire the grapple fixture, the system is required not to be capable of being uncoupled without damaging the payload or grappling fixture.

5.2 END EFFECTOR CONCEPTS

The following two concepts have been designed to meet the above requirements and will be fabricated and tested at JSC.

The manipulator end effector concept on Figure 5-1 is a device utilizing two shafts one inside the other. There are four grappling mechanisms each having two linkages located 90° apart. Figure 5-1 shows only two grappling mechanisms 180° apart for clarity purposes. One bar of the mechanical linkage is attached to the outer shaft and the other bar is attached to the inner shaft. The inner shaft is extended outward with a stroke of approximately five inches and forces the grappling mechanisms out and into the back side of the payload fixture face flange. The inner shaft fits into the center socket of the payload fixture and locks the mechanism for any maneuver. Torque is transmitted from the end effector to the payload with semi-spherical headed bolts mounted in the ends of the grappling arms that fit in holes in the face flange. These holes are located in the face flange every 10° so that during contact of the grappling mechanism and the payload fixture, the end effector has to rotate less than 10° for the bolt heads to move into the holes and lock the mechanism for its torque carrying ability (see view C-C of Figure 5-1).

MANIPULATOR END EFFECTOR CONCEPT A

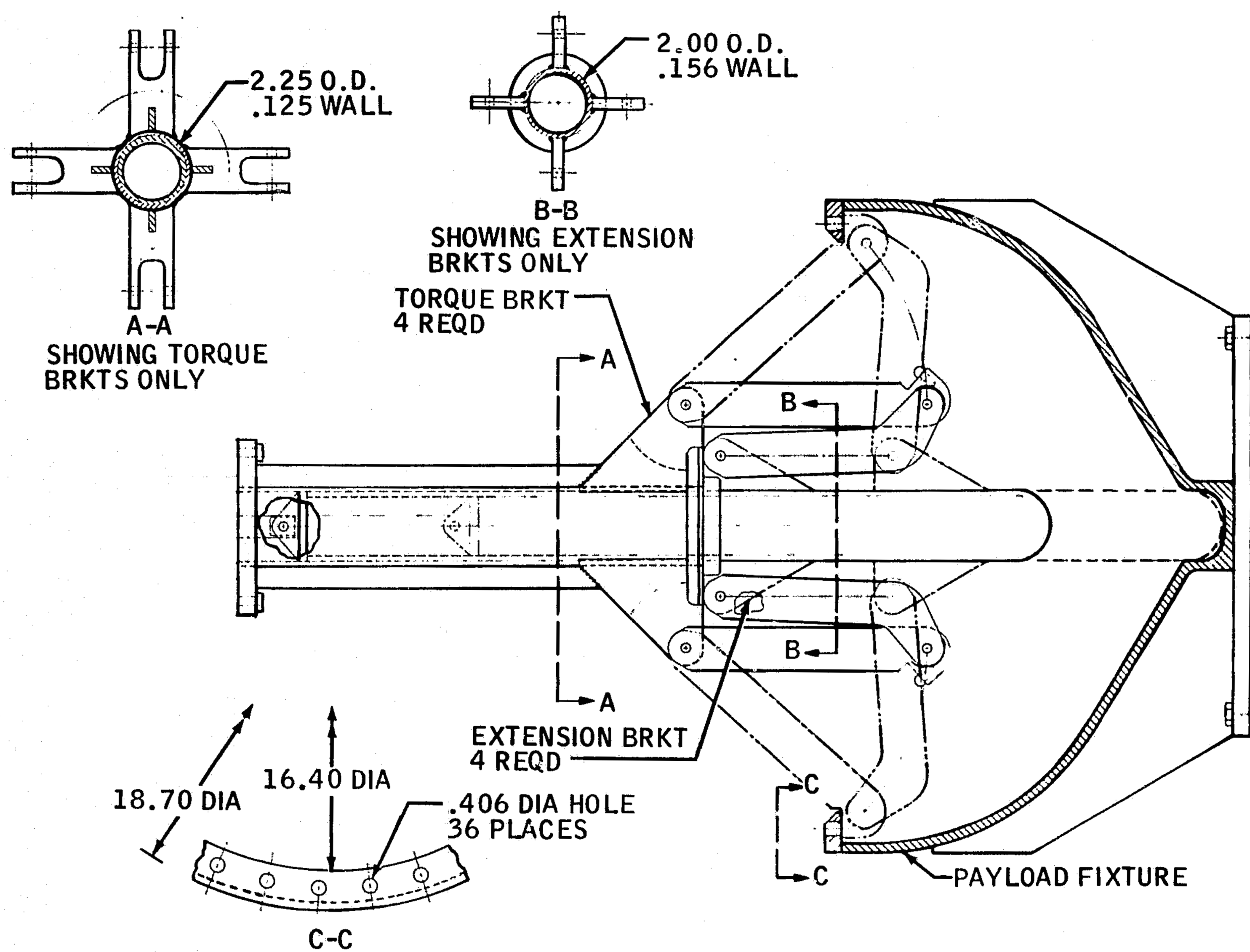


FIGURE 5-1

The hydraulic actuator is incorporated in the design of Figure 5-1 so that the end effector can be evaluated in the JSC one-g simulation facility. For actual flight design, the mechanism can be actuated by an electro-mechanical device in place of the hydraulic actuator.

Another concept of the manipulator end effector is shown in Figure 5-2. This concept consists basically of a cylindrical probe inserted into a square ring within the limits described in Section 5.1 which are ± 4 inches x, y, z plus $\pm 15°$ angular misalignment. Upon determining that the probe is within the bounds of the ring, the probe is deployed to the position shown in Figure 5-2. A linear actuator with approximately four inches stroke drives the guiding surfaces of the probe outward trapping the ring and forcing the ring into the apex formed by the intersection of the guiding surfaces. The four sets of guiding surfaces are driven into the corners of the square ring aligning the end effector and grapple fixture in roll. Each set of guiding surfaces consists of a four-bar linkage and a driving link which locks "over-center" in the fully deployed position.

MANIPULATOR END EFFECTOR CONCEPT B

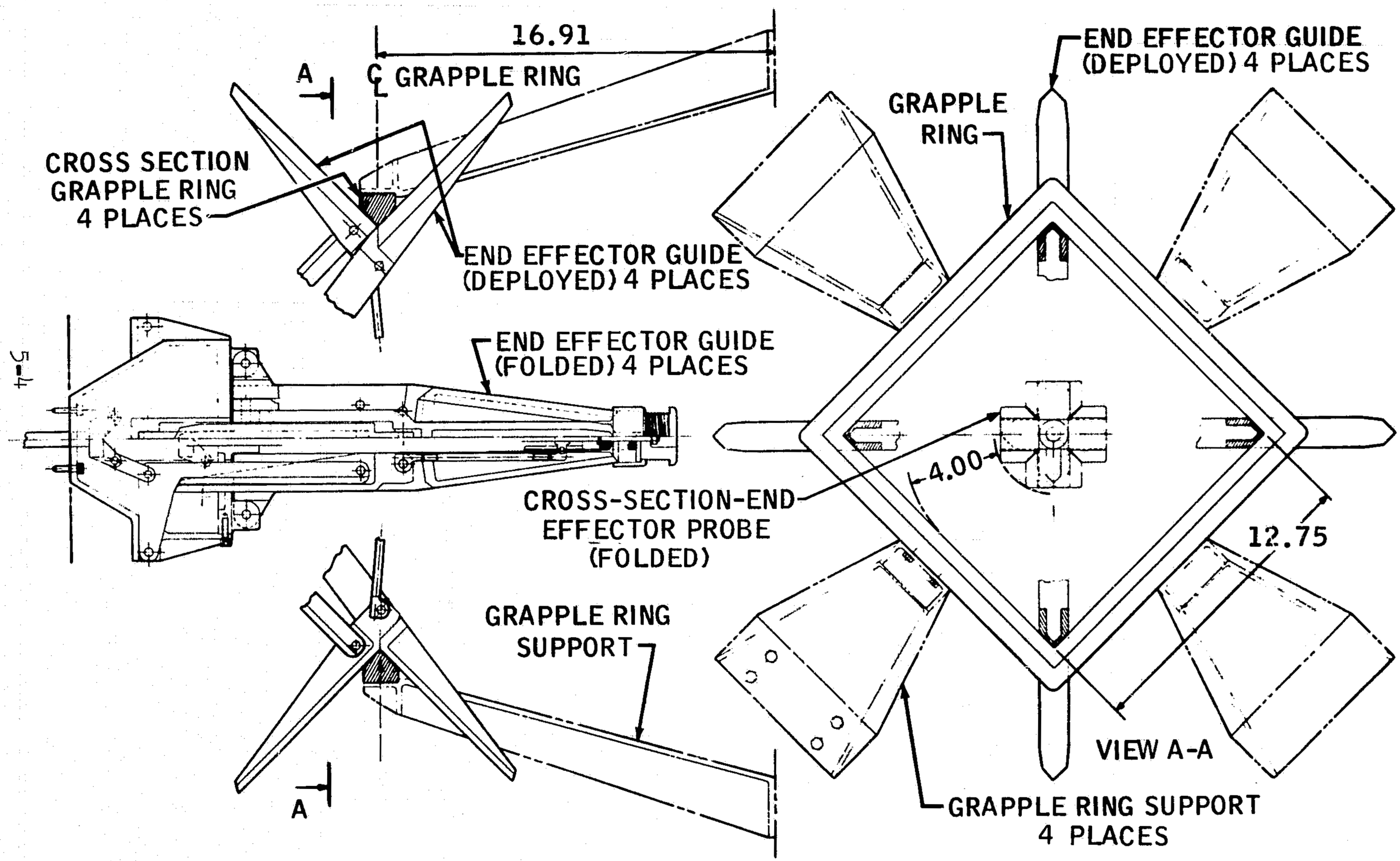


FIGURE 5-2

6.0 CONTROL SYSTEM CONCEPT

6.1 INTRODUCTION

This section of the report is concerned with control of the RMS and begins with a discussion of the control requirements, followed by a description of controllers and control methods considered. Next, a definition of the control system from a functional software viewpoint is followed by a discussion of the RMS operating modes. Finally, the section concludes with recommendations of specific problems needing investigation.

6.2 CONTROL SYSTEM REQUIREMENTS

The RMS control system will be required to operate the manipulator arm over the range from unloaded to loaded with a 65,000-pound payload. Further, operational time constraints on payload handling exist for certain planned missions. The arm design reflects an articulated arm 50 feet in length with six limited degrees of freedom: two at the shoulder, one at the elbow, and three at the wrist. In Section 4.0, the design joint torques and rates are given in Table 4-I. Finally, and possibly the most stringent requirement, is the fact that the limited Orbiter RMS control weight demands a light arm which will be inherently flexible and thereby limit the joint torque capability.

Using this information in conjunction with the RMS arm model on Figure 6-1 and a 32,000-pound payload (the design payload), some indication of the effective inertia seen by each joint as a function of the arm geometrical configuration and the payload configuration can be obtained. This is given on Table 6-I along with the design stall torque available at each joint. The inertia variations are large even for like (loaded or unloaded) configurations. By looking at the stall torque divided by the inertias in each column for each joint, one can see that large changes in control authority that the control system will be required to cope with. A summary chart of the inertia variations is given on Table 6-II.

From Table 4-I, the acceleration time to full speed can be determined for each joint with the arm fully extended, a 32,000-pound payload attached, and the Shuttle inertially fixed. The torque/inertia ratio will increase and acceleration time to full speed decrease as the geometrical configuration of the RMS changes, which defines the need for geometrically modeling the RMS. Two additional points should be made about the acceleration times. To meet these time requirements, full torque would have to be applied to the joint for 20 seconds, and when the required speed is attained, the torque would be removed or reduced to a value to overcome losses in the system. This indicates nonlinear operation of the joints. Second, the ability of the RMS operator to cope with these slow motions and delays is presently unknown and suggests the desirability of automatic modes, particularly for large payload motions.

RMS ARM MODEL

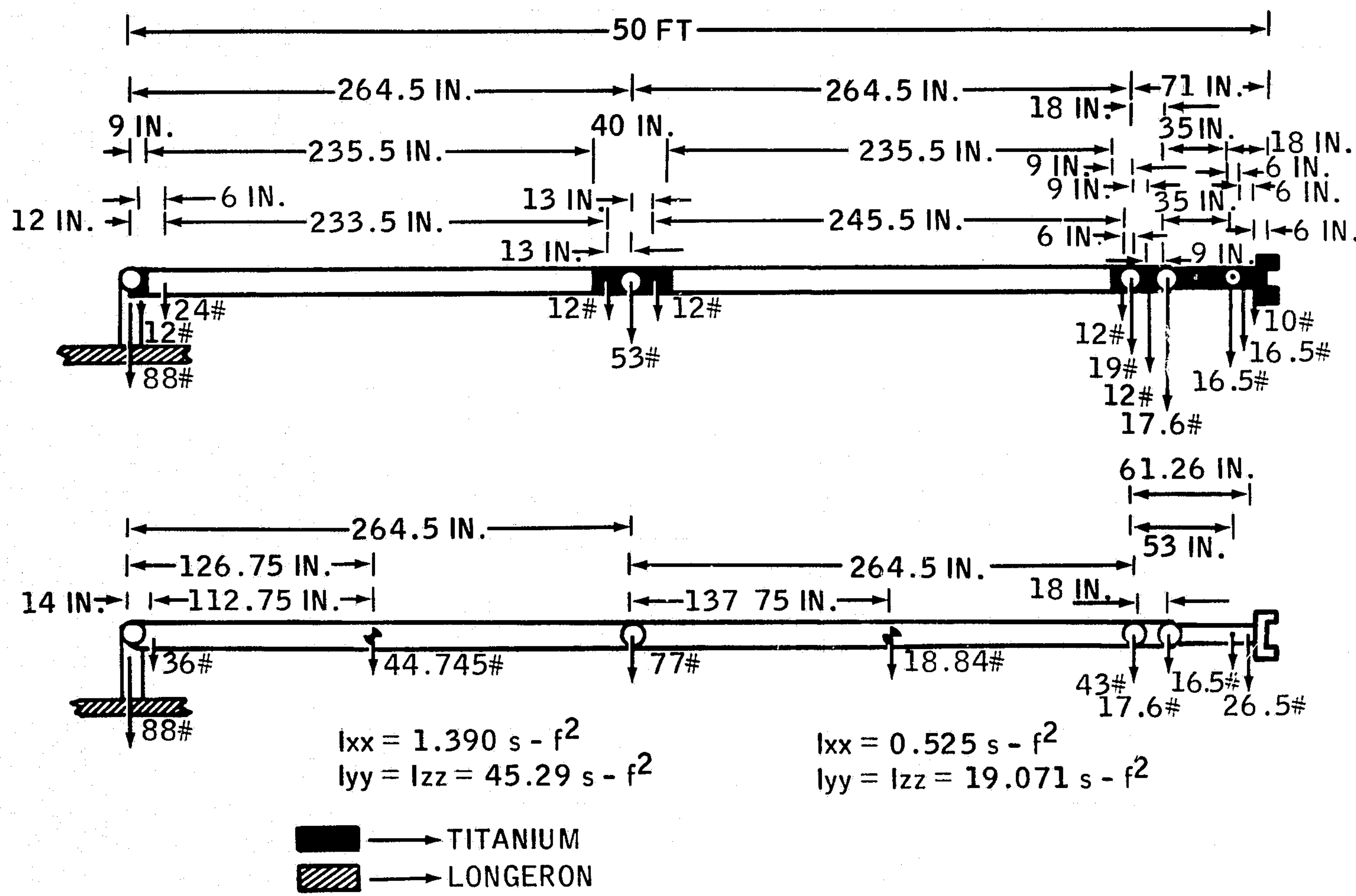


FIGURE 6-1

TABLE 6-I

MANIPULATOR JOINT APPROXIMATE INERTIA

	SHOULDER YAW	SHOULDER PITCH	ELBOW PITCH	WRIST PITCH	WRIST YAW	WRIST ROLL
TORQUE, STALL (FT-LB)	772	772	502	231	213	213
MAXIMUM INERTIA UNLOADED (SLUG-FT^2)	8,967	8,967	2,013	33	15	--
MINIMUM INERTIA UNLOADED (SLUG-FT^2)	12	1,593	953	2	15	--
MAXIMUM INERTIA LOADED (SLUG-FT^2) *	3,606,792	3,606,792	1,563,608	491,031	453,251	312,111
MINIMUM INERTIA LOADED (SLUG-FT^2) *	100,731	86,573	397,753	206,839	169,090	312,111

* ASSUMES 32,000 LBS HOMOGENEOUS CYLINDRICAL PAYLOAD 15 FT IN DIAMETER AND 60 FT IN LENGTH

TABLE 6-II

MANIPULATOR JOINT INERTIA VARIATION SUMMARY

	RATIO OF MAXIMUM INERTIA LOADED TO MINIMUM INERTIA UNLOADED [a]	RATIO OF MAXIMUM TO MINIMUM INERTIA [b]	
		LOADED	UNLOADED
SHOULDER YAW	3×10^5	35	750
SHOULDER PITCH	2×10^3	41	5
ELBOW PITCH	1.6×10^3	4	2
WRIST PITCH	2.5×10^5	2.4	16
WRIST YAW	3×10^4	2.5	1.0
WRIST ROLL	N/A	1.0	1.0

(a) FUNCTION OF GEOMETRY AND ARM LOADING
(b) FUNCTION OF GEOMETRY ONLY

6.3 CONTROLLER DEVICES AND CONTROL METHODS

Manual control of the RMS will be through a multiple degree-of-freedom controller device(s). Two types of controller devices were under consideration during this study: hand controllers, or displacement type controllers, and replica, or master-slave type controllers. The first approach consists of two three degree-of-freedom controllers similar to spacecraft controllers. Another option being considered and which needs to be further studied is one six-degree-of-freedom controller. The second type of controller, as the name implies, replicates or resembles the manipulator arm. Each of these devices has associated with it a method of control. The hand controllers represent a rate system, that is, the speed of the Remote Manipulator Arm is proportional to the displacement of the controller. The replica controller represents a position system, that is, the position of the master arm commands the position of the slave arm, with force or tactile feedback.

6.3.1 Resolved Rate Control

Resolved Rate control represents a rate system where the motion of the end effector or some other pre-selected reference can be driven in a rectilinear translational motion at a rate proportional to the deflection of the translational hand controller, and a rotational rate proportional to the deflection of the rotational hand controller. Essentially, Resolved Rate relates translational and rotational commands of the reference system to the Remote Manipulator arm joint angle rates in a manner where the commanded motion of the reference system is obtained. Resolved Rate is documented in MIT CSDL MATT Memo #63 "Documentation of Resolved Rate Control for the MSC Shuttle Arm". Figure 6-2 shows the Resolved Rate reference system located in the end effector. It should be noted that the commands move with the orientation of the end effector. For example, if the end effector were in the horizontal plane with respect to the Shuttle, a plus X command would move parallel to the Shuttle X axis, as shown on Figure 6-3(a). If the end effector were rotated 90° down, a plus X command would be in the Shuttle Z direction, Figure 6-3(b). This particular axis system should be exceedingly useful for the satellite capture task if a camera is attached to the end effector. However, it would be useless once a payload is attached. Further, an operator-oriented system would be better for grappling a payload in the cargo bay because the operator is aware of his orientation with respect to the payload. Two other more appropriate reference systems for payload manipulation and grappling of the payload in the cargo bay are Resolved Rate about a reference system located in the payload and the Orbiter reference system transposed to the base of the manipulator shoulder joints.

6.3.2 Replica Control

The replica control system with force feedback is a position control system consisting of two major parts: the Remote Manipulator Arm, or slave arm; and the control arm, or master arm. The slave arm is a 50 ft long boom with

MANIPULATOR END EFFECTOR AXIS SYSTEM

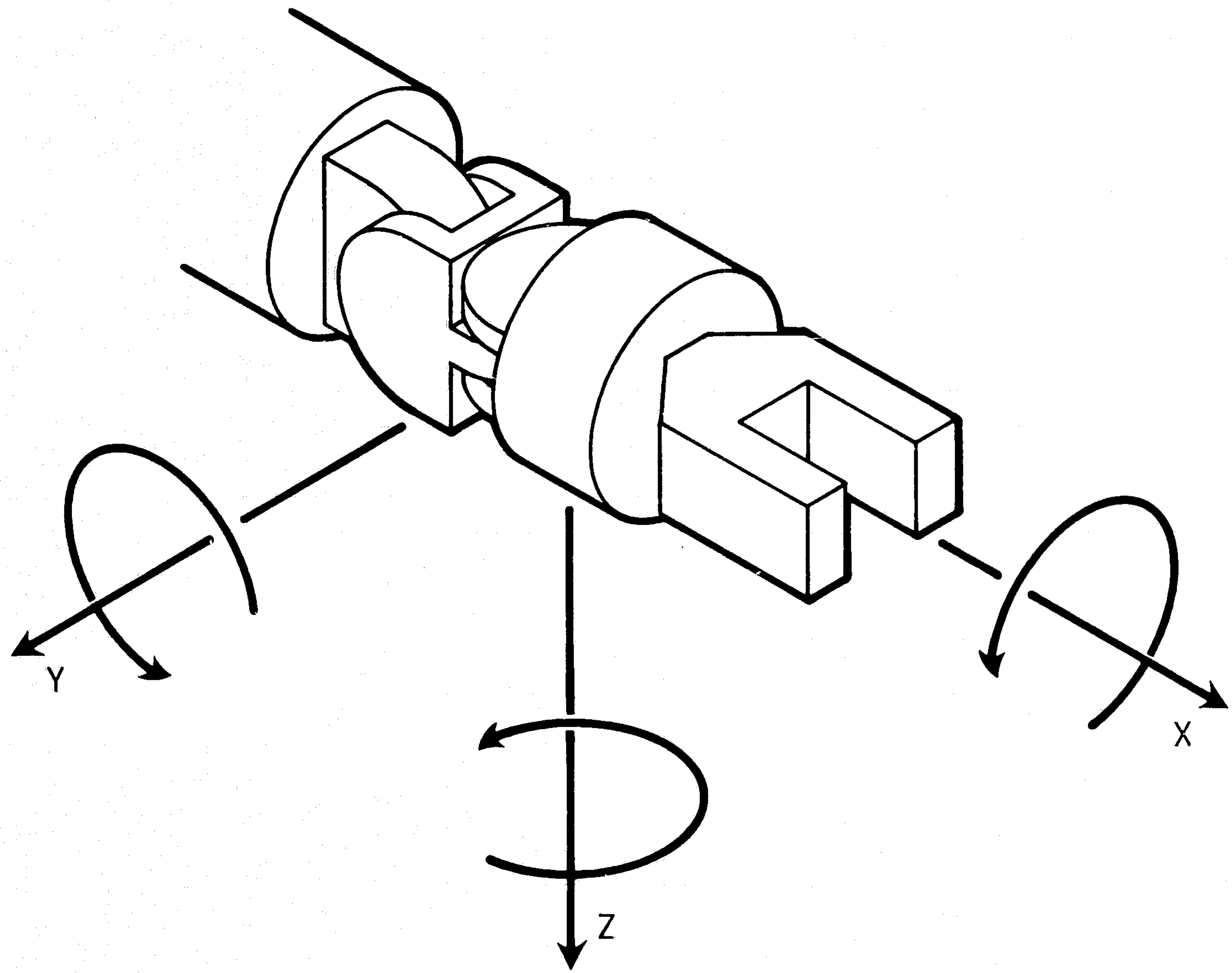


FIGURE 6-2

RESOLVED RATE MOTION
WITH MANIPULATOR END EFFECTOR ORIENTATION

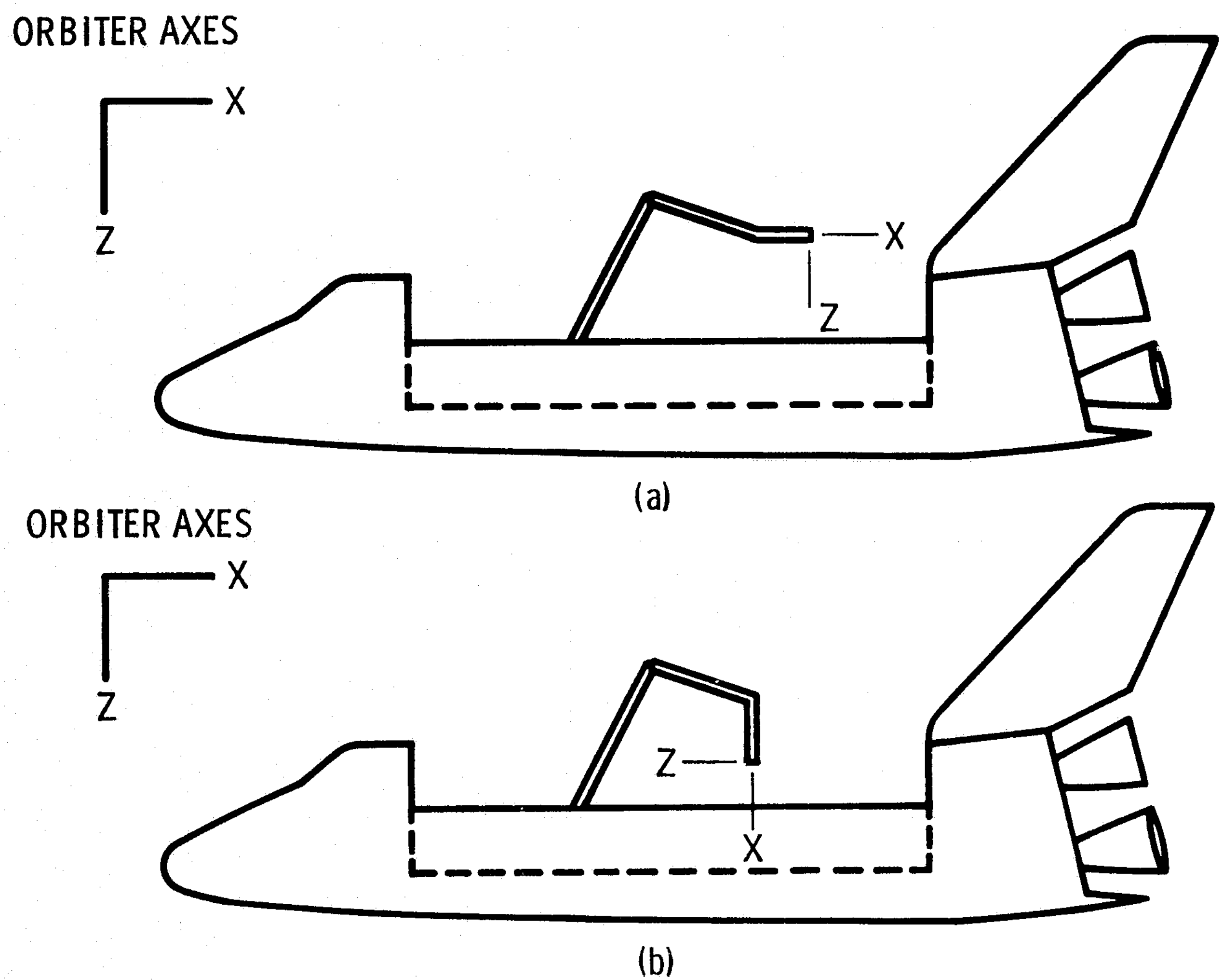


FIGURE 6-3

six degrees of freedom and has been described previously. The master arm, since it replicates the slave, has essentially the same characteristics except it is much smaller in size. The fact that the system is bilateral means that forces acting on either end of the master or slave system are sensed at the other end.

Replica control systems have been used for earth-based applications such as "hot room" teleoperator applications where the master and slave are about the same size. Because of the size of the RMS slave arm, however, the master arm will be much smaller than the slave. The aft crew station configuration limits the replica master to about 1:20 scale. The master arm would be approximately 2.5 ft long when fully extended. However, this large ratio produces a system that magnifies the operator's inputs making precise positioning of payloads difficult.

To achieve full range of motion of the manipulator, the operator could get into some awkward and uncomfortable positions with the replica controller since the controller would have to be positioned in the same positions the slave would assume. To cope with these two situations, two requirements for replica control for the Shuttle RMS would be variable gain master-slave and indexing.

Variable gain master-slave allows for different sensitivities between the master and slave. For large motions of the slave arm the high ratio such as the 1:20 would be used. Accordingly, a one-foot movement of the master would give a twenty-foot movement of the slave. For precise positioning, a lower ratio such as 1:5 would be used for a one-foot movement of the master to provide a five-foot movement of the slave.

Indexing is a means by which the master can be relocated for maximum operator convenience regardless of slave position. Also, indexing would allow gross motion of the slave in low gain ratio.

Both of the above requirements for master-slave operation of the RMS on the Shuttle have one major disadvantage. The spatial correspondence between the master and slave, which is very basic to the master-slave concept, is destroyed. Figure 6-4 shows schematically a replica system as it would be envisioned on the Shuttle.

6.3.3 Controller Device/Control Method Recommendation

Based upon present knowledge and simulation work the recommendation for a controller device and control method is hand controllers using Resolved Rate. Two three degree-of-freedom controllers will be used unless additional study shows that one six degree-of-freedom controller can be adequately mechanized and is considered necessary.

6.4 REMOTE MANIPULATOR CONTROL SYSTEM (FUNCTIONAL SOFTWARE DESIGN)

The discussion in Section 6.2 points toward the necessity for performing certain functions for control of the Remote Manipulator. Figure 6-5 shows the present concept for control of the Remote Manipulator based on the previous discussion

RMS MASTER/SLAVE CONTROL SYSTEM

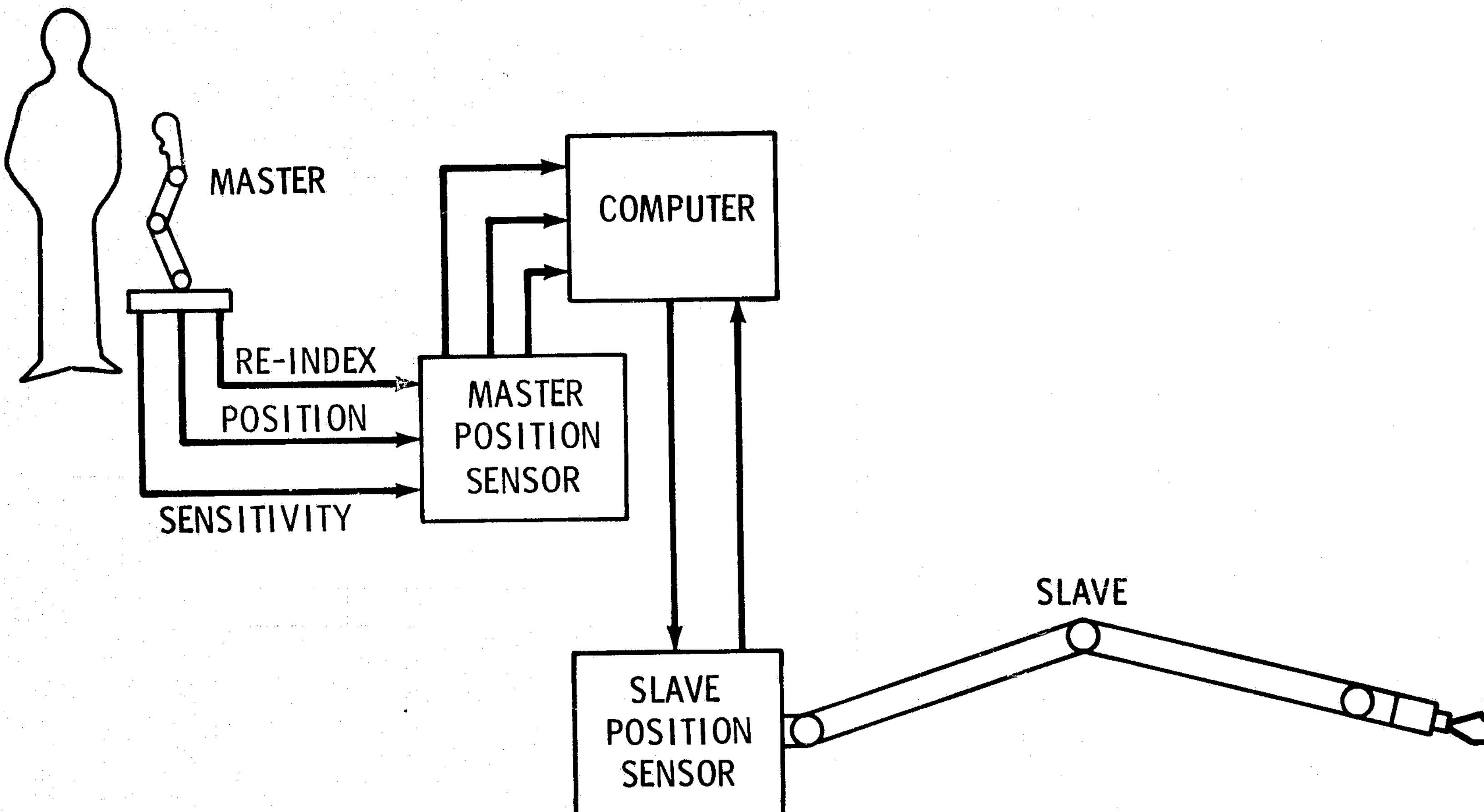


FIGURE 6-4

REMOTE MANIPULATOR CONTROL SYSTEM

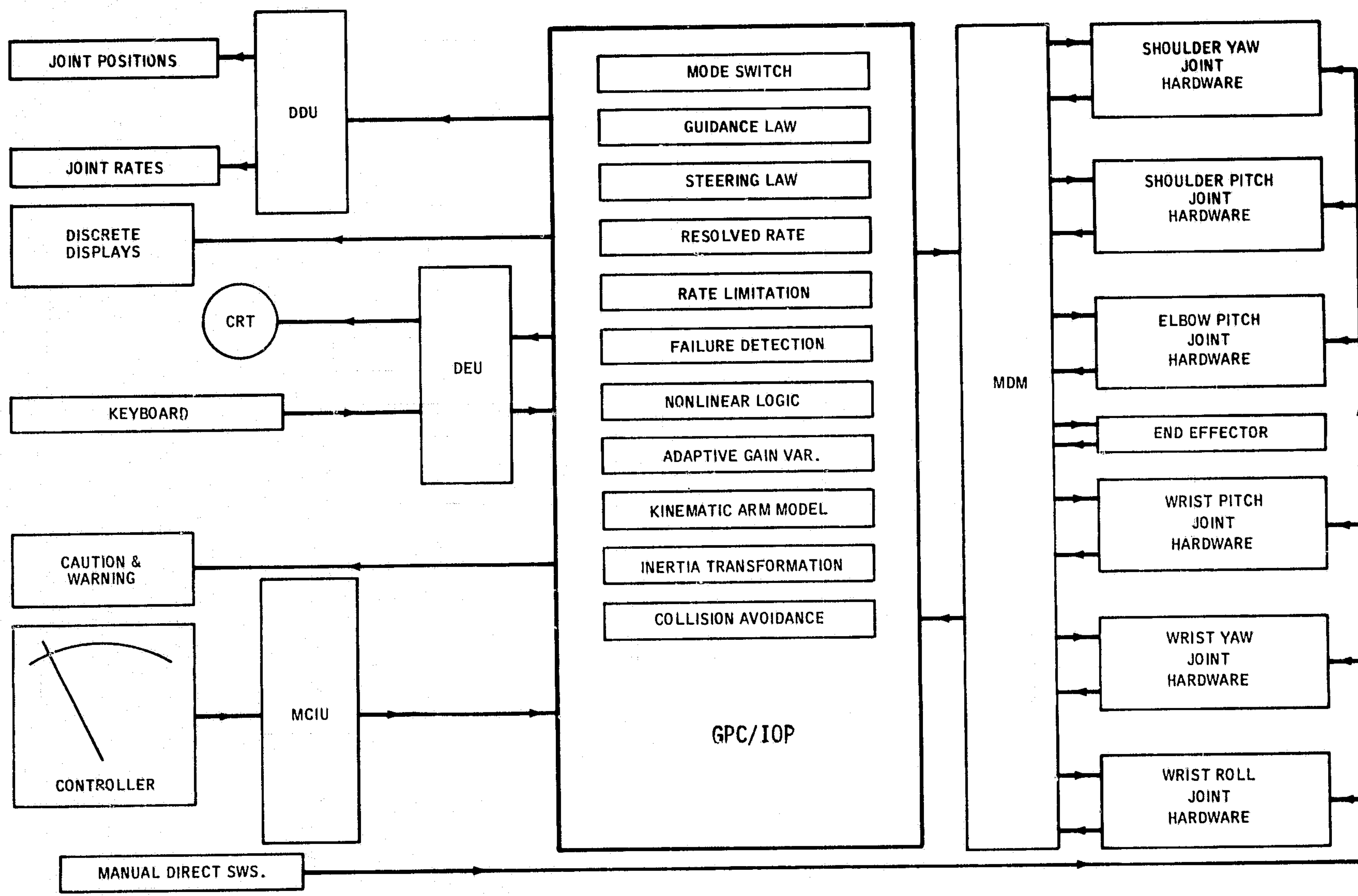


FIGURE 6-5

and present sensors - position sensor and rate tachometer. The joint hardware and end effector designs were discussed in Section 4.0 and 5.0. The controller was discussed in this section and the displays will be shown in Section 11.0. The discussion here will be limited to necessary functions for the control of the RMS and presently envisioned to be resident in the General Purpose Computer (GPC). The following discussion provides only a structural breakdown of those functions necessary to the solution of the Remote Manipulator control problem. The control software is broken down into 11 pieces or blocks, each of which will be discussed briefly.

6.4.1 Mode Switch

This block of software represents a simple logic box that will indicate to the remainder of the software which of the three RMS modes are operating. The three modes are: automatic, manual, and manual direct.

The blocks, "Guidance Law" and "Steering Law", are only applicable to the Automatic Mode.

6.4.2 Guidance Law

In this block of software would be the algorithms necessary for generating the trajectories for required manipulator motion. Three possible types of trajectories are pre-stored, predictive, and real-time.

Pre-stored trajectories are simple paths stored in the computer for tasks that are predetermined before flight. Predictive trajectories are trajectories where the end conditions are given and an acceptable trajectory is determined before the arm is moved. Real-time trajectories are trajectories where the end conditions are given and the trajectory is developed as the motion is taking place.

Input to "Guidance Law" would be a discrete requesting a pre-stored trajectory or the end conditions for predictive or real-time trajectories.

6.4.3 Steering Law

In this block of software the trajectory obtained in "Guidance Law" would be broken down into commands acceptable to the control system for smooth motion.

6.4.4 Resolved Rate

Resolved Rate Control was discussed earlier, and this block of software provides the mechanization for Resolved Rate.

Input to "Resolved Rate" would be the command coordinate system. The three options presently being considered are the end effector coordinate, manipulator base coordinate, and payload oriented coordinate systems.

6.4.5 Rate Limitation

The output of "Resolved Rate" is the individual joint rate commands. These are generated without regard to limitations of the joint hardware. This block of software would insure that the joint rates requested from "Resolved Rate" would be acceptable for the design constraints. If necessary, this block of software would scale all the joint rate commands to insure coordinated motion.

6.4.6 Failure Detection

This block of software compares the joint commands and outputs to determine whether a joint has failed. Further, some type of display would be given to the operator as well as an indication to other software blocks that a joint had failed.

The next four blocks, "Nonlinear Logic", "Automatic Gain Variation", "Kinematic Arm Model", and "Inertia Transformation", are concerned with the previously discussed parameter variation problem. "Kinematic Arm Model" and "Inertia Transformation" are intended to model the physical parameters. "Nonlinear Logic" and "Adaptive Gain Variation" are intended to change the control system parameters to cope with the physical parameter variation.

6.4.7 Kinematic Arm Model

This block of software would provide a mathematical description of the geometrical changes of the Remote Manipulator Arm and payload, if any, as a function of the joint angles. Input to this block of software would be arm and payload physical properties.

6.4.8 Inertia Transformation

This block of software would provide the inertia transformations of the arm and payload as a function of the joint angles for deriving the effective inertia seen at each joint. Input to this block of software would also be arm and payload physical properties.

6.4.9 Nonlinear Logic

This block of software would provide the logic for acceleration command of the joints to the required speed in the least possible time as well as sustain that speed as required.

6.4.10 Automatic Gain Variation

This block of software would provide the necessary servomechanism system gain variations and compensation, if necessary, for dealing with the payload physical property changes and arm geometrical configuration.

6.4.11 Collision Avoidance

This block of software would provide the algorithms for predicting a collision. Inputs to this block of software would be physical properties of any bodies in the operating envelope of the manipulator and payload.

6.5 REMOTE MANIPULATOR SYSTEM OPERATING MODES

The Remote Manipulator System will be capable of being operated in three different modes: Automatic Mode, Manual Mode, and Manual Direct Mode.

6.5.1 Automatic Mode

The Automatic Mode allows for movement of the unloaded arm (no payload) or loaded arm (arm and payload) without manual interface through the controller. As discussed in Section 6.4 "Guidance Law", two possible types of movement are possible in this mode.

First, a predetermined trajectory or path to get the end effector or payload from a present position and orientation to the desired position and orientation would be stored in the GPC. The operator either by DSKY entry or some other mechanization would "call up" the trajectory. The trajectory would be automatically input to the Remote Manipulator control system.

The second type of movement possible would be similar to that discussed previously except the desired position and orientation are not known prior to launch. In this instance the operator would input the required position and orientation of the end effector or payload and a trajectory would be generated. Two possible means of implementation are generating a "safe" trajectory that has avoided collisions prior to any motion of the end effector or payload, and generating the trajectory while the end effector or payload is in motion toward the desired position and orientation checking for possible collisions as the trajectory is transversed.

The following tasks given on Figure 6-6 could be accomplished using the Automatic Mode.

<u>Unstow Arm</u> - Entails rotating the manipulator arm, retention fittings, and shoulder attach fitting outboard as discussed in Section 8.0

RMS AUTOMATIC CONTROL MODE

- UNSTOW ARM
- DEPLOY ARM
- MANEUVER ROUTINE
  - MANEUVER UNLOADED ARM TO ANY SPECIFIED POSITION (INSPECTION)
  - MANEUVER ARM TO ANY SPECIFIED POSITION TO PREPARE FOR MANUAL GRAPPLING
  - MANEUVER P/L TO ANY SPECIFIED POSITION AFTER MANUAL P/L GRAPPLING
  - MANEUVER P/L TO P/L INSTALLATION AND DEPLOYMENT AID (PIDA)
  - MANEUVER P/L INTO BAY USING PIDA
  - MANEUVER P/L INTO P/L BAY WITHOUT USING PIDA (LARGER ALLOWABLE CLEARANCES)
  - RETURN TO PRE-DEPLOY POSITION
- SECURE ARM
- STOW ARM

FIGURE 6-6

Deploy Arm - Entails the release of the manipulator arm from the retention fittings

Maneuver Routine - Entails the movement of the arm and payload, if any, from one point to another. The tasks specified in Figure 6-6 are self-explanatory.

Secure Arm - Entails the securing of the Remote Manipulator arm to the retention fittings

Stow Arm - Entails the rotating of the manipulator arm, retention fittings and shoulder attach fitting inboard so that the RMS will be in the envelope of the cargo bay for closing of the cargo bay doors

As the first two tasks, "Unstow Arm" and "Deploy Arm", and the last two tasks, "Secure Arm" and "Stow Arm", do not involve manipulation, the mode used is immaterial.

6.5.2 Manual Mode

The Manual Mode allows for the movement of the unloaded or loaded Remote Manipulator arm through manual input using the controller. The present recommendation reflects hand controllers; however, whether one controller with six degrees-of-freedom or two controllers with three degrees-of-freedom each has not been determined. Used in conjunction with the hand controller is Resolved Rate control, which has been discussed previously. The tasks which can be accomplished in the manual mode are outlined on Figure 6-7. The first two and last two do not reflect manipulation of the arm and are independent of the mode. The remainder of the tasks on Figure 6-7 using the hand controllers and Resolved Rate are equivalent to those tasks given on Figure 6-6, Automatic Mode, with two notable exceptions, grappling of the payload and insertion of the payload into the payload handling device. Both of these tasks are envisioned as being accomplished only under manual control.

6.5.3 Manual Direct Mode

The manual direct mode would allow movement of the Remote Manipulator Arm on a joint-by-joint basis using hard wired switches located on the control panel to command the joints. The computer would be bypassed completely. For effective use of this mode, high accuracy joint position displays are required that do not depend upon the computer.

The most likely uses of this mode would be to stop the manipulator in the event of a computer failure and return the arm to the pre-deploy position in an emergency situation.

6.6 RECOMMENDATIONS

The Remote Manipulator control system requirements have been described and a control system functional design given. Much more work is required before any specific design is completed and algorithms developed. A study of servo system

RMS MANUAL CONTROL MODE

- UNSTOW ARM
- DEPLOY ARM
- MOVEMENT OF THE UNLOADED ARM USING RESOLVED RATE
- GRAPPLE OF P/L
- MOVEMENT OF THE LOADED ARM USING RESOLVED RATE
- INSERTION OF P/L INTO PIDA
- MOVEMENT OF THE P/L INTO THE BAY USING THE PIDA
- MOVEMENT OF THE P/L INTO THE BAY WITHOUT THE USE OF THE PIDA
- SECURE ARM
- STOW ARM

FIGURE 6-7

design to cope with widely varying plant parameters is required. Further studies on low control authority and flexibility should be given high priority. Finally, the development of a collision avoidance scheme that insures bodies, including the arm itself, in the Remote Manipulator Arm operating envelope will not collide may be one of the most formidible problems yet to be solved.

With regard to simulations, two significant areas must be addressed quickly, RMS dynamics and manual control of the loaded arm. First, almost all of the analysis done to date on the RMS has been rigid body analysis. The effects of structural flexibility and joint flexibility could have minimal or significant effect on the present mechanical design. The RMS is so complex that only a complete flexible body simulation can determine the effects. Similarly, the effects of Shuttle motion and the Shuttle control system on the RMS and vice versa must be evaluated. Second, the area of manual control of the loaded arm will have an immense effect on the control system requirements, and an accurate simulation is needed. For example, delays in obtaining commanded motion and inadequate visual perception could drive the design to a high degree of automation as well as increased sophistication of the algorithms.

7.0 ELECTRICAL POWER

7.1 GENERAL CONSIDERATIONS

Rockwell specification MF 0004-002 defines the characteristics of electrical power which will be supplied to the various subsystems and establishes the general electrical design, development, and test requirements applicable to any subsystem interfacing with the Power Distribution Subsystem. No special requirements, over and above those called out in this specification are anticipated for the interface with the RMS.

7.1.1 Redundancy

AC and DC power will be supplied from two each redundant and isolated AC and DC buses for distribution within the RMS.

7.1.2 Pyro Sequencing

Standard pyro sequencing circuits will be provided for the RMS. Due to capacity limitation of the forward MEC's mission events controllers), it may be necessary to control some of the pyro devices from the aft MEC's.

7.2 PEAK POWER REQUIREMENTS FOR MANIPULATOR ARM

Electrical power must be supplied to 12 joint motors, 2 end effector motors, 12 position indicators, 14 brakes, 1 TV camera, and 1 floodlight. The electrical power requirements listed in Table 7-I are based on peak power required for off-the-shelf motors that meet or exceed the torque required at each joint. Power required for the brakes, position indicators, TV cameras, and floodlights are estimated. The number of wires listed for each device assumes one AC power feeder for all position indicators and separate control and status indication for each of the brakes from the aft crew station.

7.3 POWER DISTRIBUTION

DC power will be supplied to the aft crew station from PCA's (power control assemblies) in the forward avionics bay (Figure 7-1). Feeders between the PCA's and aft crew station will be protected with fuses or remote power controllers and will be sized to accommodate two manipulator arm operating sequentially with one complete set of motors, one complete set of brakes, and two sets of floodlights and cameras operating simultaneously (approximately 5100 watts). Control relays for deploy and latch functions will be provided in the mid body control assemblies.

TABLE 7-I
ELECTRICAL POWER AND WIRING REQUIREMENTS

LOAD	NUMBER OF UNITS	WATTS PER UNIT	TOTAL WATTS (PEAK)	WIRES PER UNIT	TOTAL WIRES	COMMENTS
SHOULDER JOINT						
MOTORS	4	91	364(DC)	2	8	
TACHOMETERS	4	---	---	2	8	
BRAKES	4	10	40(DC)	[a]4	16	a. 2 POWER, 2 D&C
POSITION INDICATORS	4	2	8(AC)	4	16	
ELBOW JOINT						
MOTORS	2	49	98(DC)	2	4	
TACHOMETERS	2	---	---	2	4	
BRAKES	2	10	20(DC)	4	8	
POSITION INDICATORS	2	2	4(AC)	4	8	
WRIST JOINT						
MOTORS	6	49	294(DC)	2	12	
TACHOMETERS	6	---	---	2	12	
BRAKES	6	10	60(DC)	4	24	
POSITION INDICATORS	6	2	12(AC)	4	[b]26	b. INCL AC POWER FEEDER
END EFFECTOR						
MOTORS	2	49	98(DC)	2	4	
TACHOMETERS	2	---	---	2	4	
BRAKES	2	10	20(DC)	4	8	
TV CAMERA	1	25	25(DC)	[c]6	6	c. INCL 2 SHIELDED PAIR
FLOODLIGHT	1	150	150(DC)	2	2	
TOTAL PER RMS			[d]1,169(DC) 24(AC)		170	d. DOES NOT INCL D&C

RMS ELECTRICAL POWER DISTRIBUTION

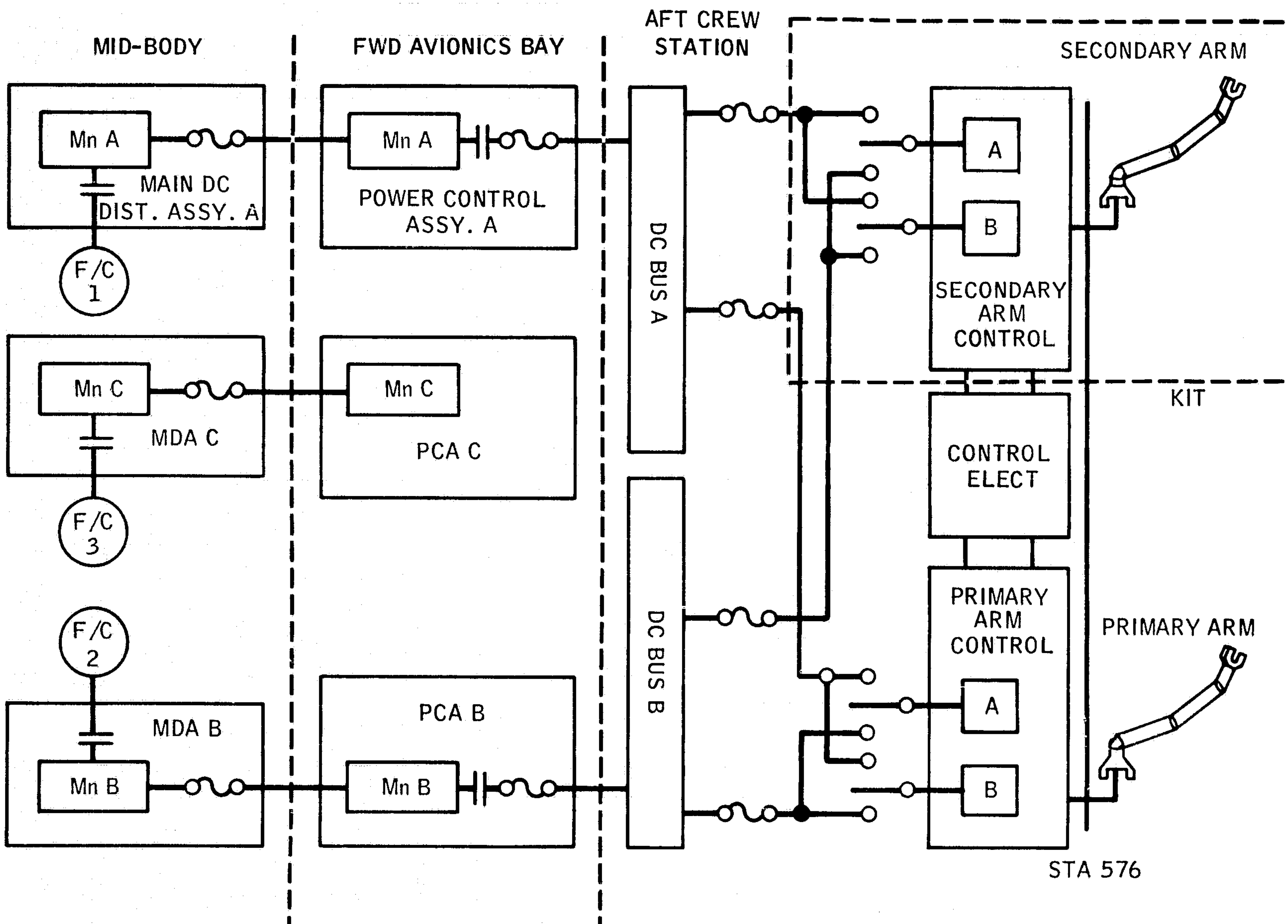


FIGURE 7-1

7.4 PYRO SEQUENCING

Standard pyro sequencing will be incorporated in the forward and aft MEC's. The electrical cable bundle will be separated by the arm pyro device.

7.5 WIRE ROUTING THROUGH ARM

The wire bundle, consisting of approximately 170 wires at the base, will be routed up through the arm and past the rotating joints. Based on a study made by Lockheed Missiles and Space Corporation under Contract NAS 9-11039, "Evaluation of Space Station Solar Array Technology and Recommended Advanced Development Programs," all spacecraft flown in the past having a requirement to transfer power across a rotating joint have used slip rings where the rotation is continuous and flex cable where the rotation does not exceed 440°. The later would seem to be the most logical approach for transfer of power to the motor joints. Slip rings may be necessary for the end effector because the wrist roll joint will be continuous rotation.

7.6 CONTROL ELECTRONICS

Figure 7-2 shows a schematic of the control electronics associated with a typical two-motor manipulator joint. In this arrangement, the electronics are located remotely in an avionics bay with only position and velocity transducers located in the arm with the joint mechanical system. Both DC and AC power service are shown on the schematic. The AC service may or may not be required and will depend upon the selection of specific transducers.

The electronic configuration is composed of an "A" side and an identical "B" side. A redundant comparator function monitors and compares selected parameters from A and B systems. If either, or both, of the comparators detect an out-of-tolerance condition, a display is activated at the operator's station, and deactivation of the joint and/or the complete arm is initiated. In the schematic shown, the motor brakes are enabled through a separate operator controlled switch and are not applied automatically as part of the control electronics function. Before reactivating the joint, the operator must perform a yet undefined diagnostic check to determine which system is operable.

The mechanization of Figure 7-2 is for joint rate control with motor speed feedback as part of the inner loop. Position information, which has no inner loop function in this mechanization, is returned to the general-purpose computer for the "resolved rate" control calculations. A position control or combined position/rate control mode would require an alternate mechanization.

MANIPULATOR JOINT CONTROL ELECTRONICS

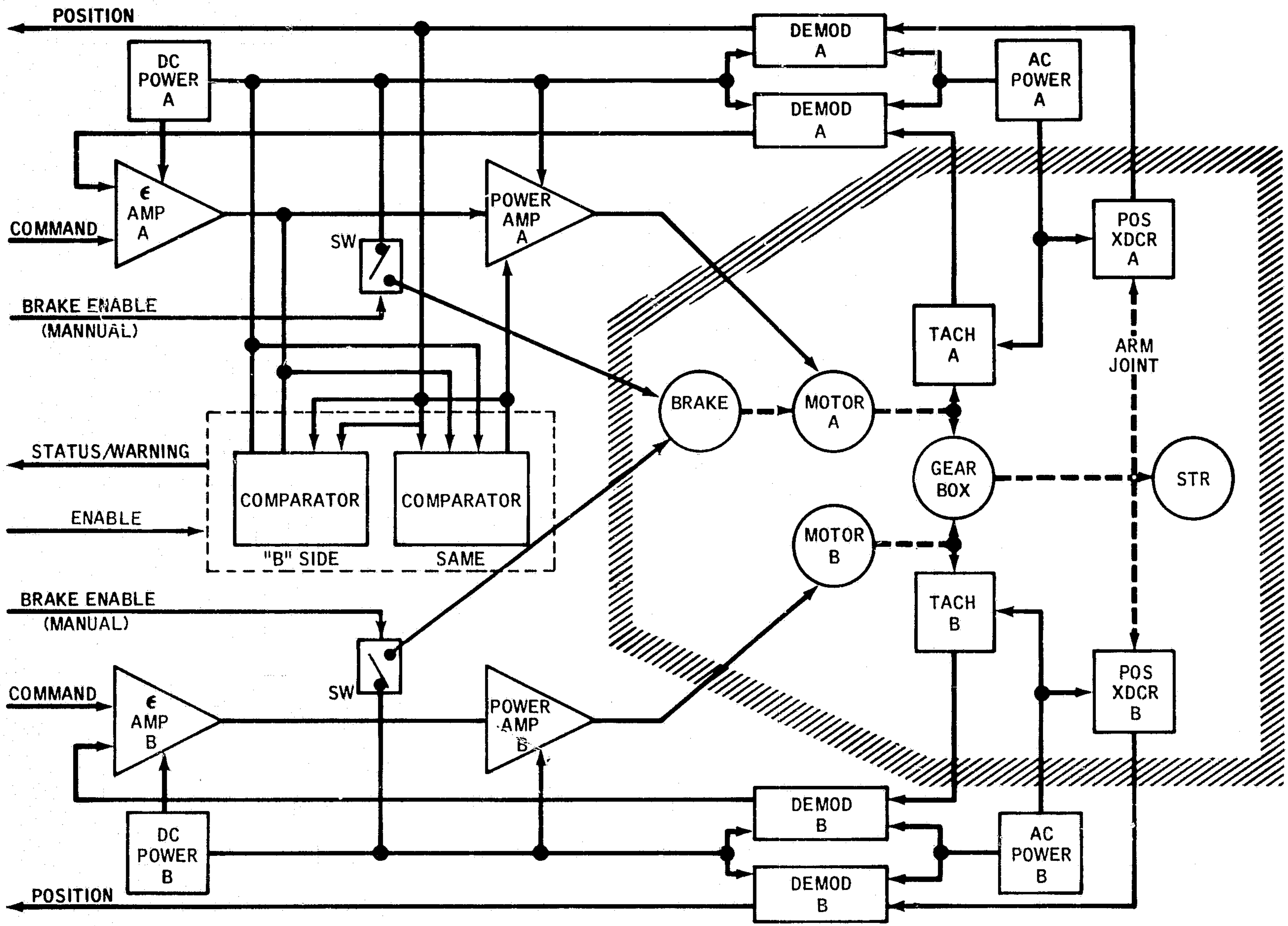


FIGURE 7-2

8.0 MANIPULATOR DEPLOYMENT/RETENTION SYSTEM

The manipulator deployment/retention system shall consist of four separate structural systems from the manipulator to the Orbiter left/right sill longeron. These retention systems shall be located at X_0 679.5 (manipulator shoulder), X_0 911.05 (upper arm), X_0 1153.5 (lower arm), and X_0 1256.5 (wrist). See Figure 8.1. Retention at these locations shall accommodate all flight and ground deflections and loading conditions. The system shall serve as a means of deploying the manipulator outboard from its stowed position to provide payload/manipulator clearance during payload installation or removal on the ground or inflight. The manipulator shall be stowed in a straight line or extended configuration with its centerline parallel to the X direction and located at approximately Y_0 89.5 and Z_0 446. (The wrist yaw and roll joint must be locked.) The four deployment/retention systems shall contain a common pivot near the sill longeron thereby providing a "hinge" for the stowed manipulator to be deployed outboard. Once deployed inflight, the three aft systems shall release from the manipulator arm enabling it to articulate and perform its mission functions. The deployment/retention system at the manipulator shoulder (X_0 679.5) shall support all loads associated with inflight operation of the manipulator. Upon completion of the manipulator's mission functions, it shall articulate to its extended configuration and back to the three aft systems where they must capture and latch to the manipulator. Then all four systems shall rotate simultaneously to return the manipulator to its stowed position enabling the payload bay doors to close. The possibility of a failure occurring in any of the four devices that may result in the inability to close the payload bay doors in orbit necessitates a separation system at all four locations.

The deployment mechanisms shall consist of the actuators, linkages, and associated hardware required to drive the deployment/retention systems and manipulator from the stowed position to the deployed position and vice versa. All systems must lock in both positions and carry the required loads. Operation of the actuators shall be synchronized so bending moments are not introduced into the manipulator arm.

The retention mechanisms shall consist of alignment guides, latch mechanisms and associated hardware required to capture, latch and release the manipulator arm to/from the three aft deployment/retention systems. These mechanisms must carry the required loads and accommodate the inflight relative thermal and structural load deflections across this functional interface.

The separation mechanisms shall consist of that hardware, pyrotechnics, et cetera, necessary to separate the manipulator and four deployment/retention systems from the Orbiter longeron. A failure in the deployment or retention mechanisms would necessitate this separation. The separations must be made at a point such that closure of the payload bay doors is possible. The separations will be through electrical lines as well as structure. All separation hardware such as explosive bolts, nuts, clamps, et cetera, shall be captive to prevent any damage to the Orbiter. After separation, the manipulator and deployment/retention systems shall not impact the Orbiter.

MANIPULATOR DEPLOYMENT/RETENTION SYSTEM

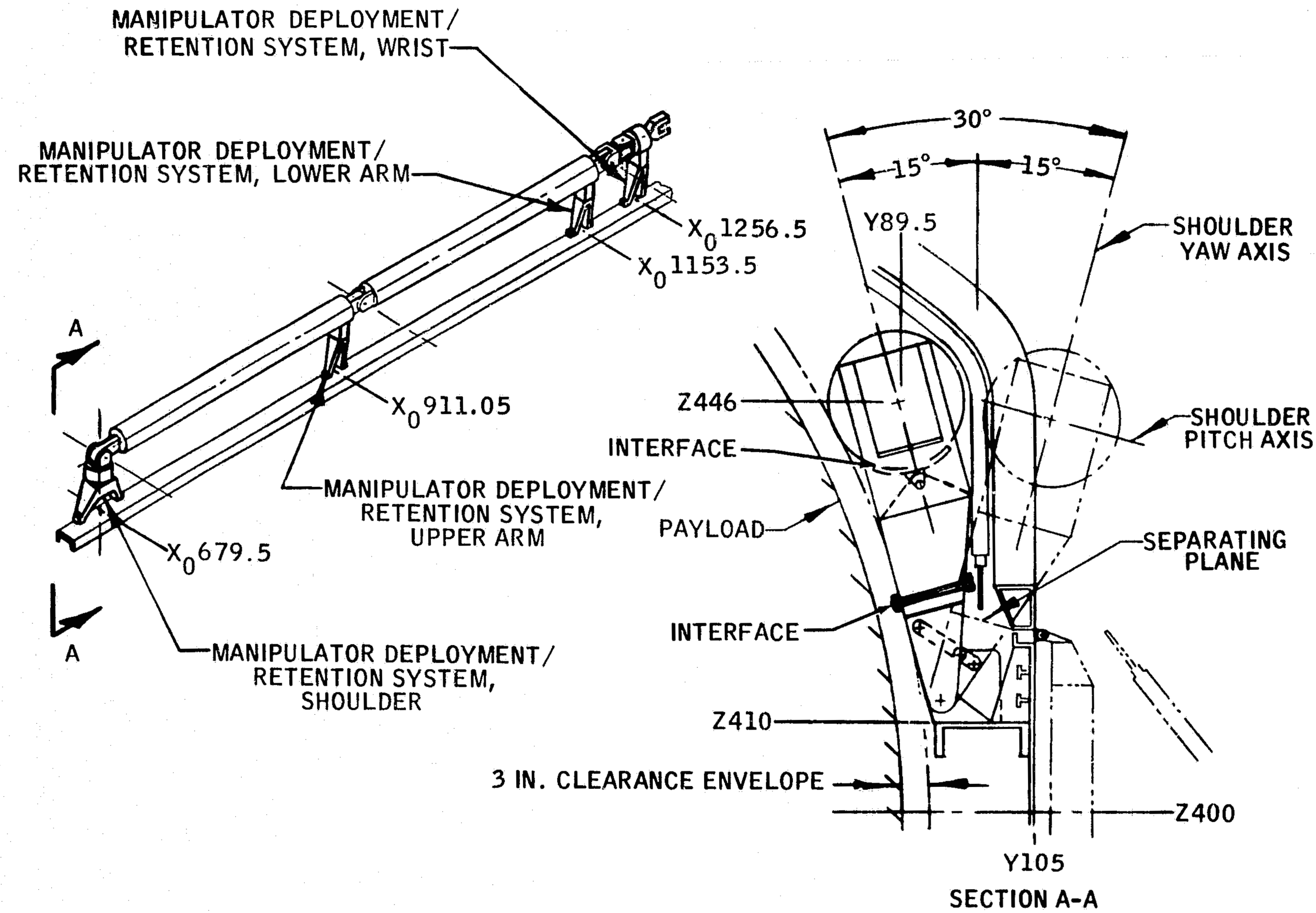


FIGURE 8-1

9.0 PAYLOAD INSTALLATION AND DEPLOYMENT AID (PIDA)

9.1 GUIDELINES

The concept design study of the RMS showed that structural deflection, position measurement error, and visibility limits made installation of a large payload into the payload bay within the ±3-inch clearance very difficult if not impossible. Simulations with the JSC simulator subjectively verified this conclusion. From the study data and the simulator experience, the following guidelines were developed for stowage of payloads into the cargo bay by the manipulator. See Figure 9-1 for nomenclature.

a. Docking points shall be located outside of the RMS critical maneuvering area while providing line-of-sight operation from the RMS operators station.

b. The sequence of operation shall provide single point capture steps rather than requiring multiple points to be captured simultaneously.

c. The PIDA shall be capable of moving the payload between the deployed and stowed positions without exceeding the 3.0-inch payload clearance envelope.

d. The existing longeron bridge fitting attachment points shall be used for the installation of the PIDA.

e. The docking points shall be designed for a ±6.0 inch lateral and ±15 degree angular misalignment at each point.

f. The PIDA shall be packaged to stow between the closed door and a 15-foot diameter payload in the payload bay.

9.2 OPERATION

The sequence of operation for payload insta lation is shown on Figure 9-2. After the payload is captured, it is positioned such that the aft probe fitting is inserted into the aft drogue. This operation is within line of sight of the RMS operator. The payload is then positioned to insert the forward probe fitting into the forward drogue. The interface is rigidized to control motion of the payloads relative to the PIDA. The manipulator is then released from the payload and positioned away from the operating area. The aid then rotates about the pivot points near the drogue, see Figure 9-3, until the payload centerline is in the position marked No. 2. At this time, the aid arms rotate about the pivot points near the longeron until the payload is in the payload bay and the retention fittings are locked. The aid arms are then relaxed to prevent their being a structural load path.

This concept has the potential capability to hold a payload while being serviced by the RMS and it also appears that a payload may be deployed without using an RMS.

NOMENCLATURE FOR
PAYLOAD INSTALLATION AND DEPLOYMENT AID CONCEPT

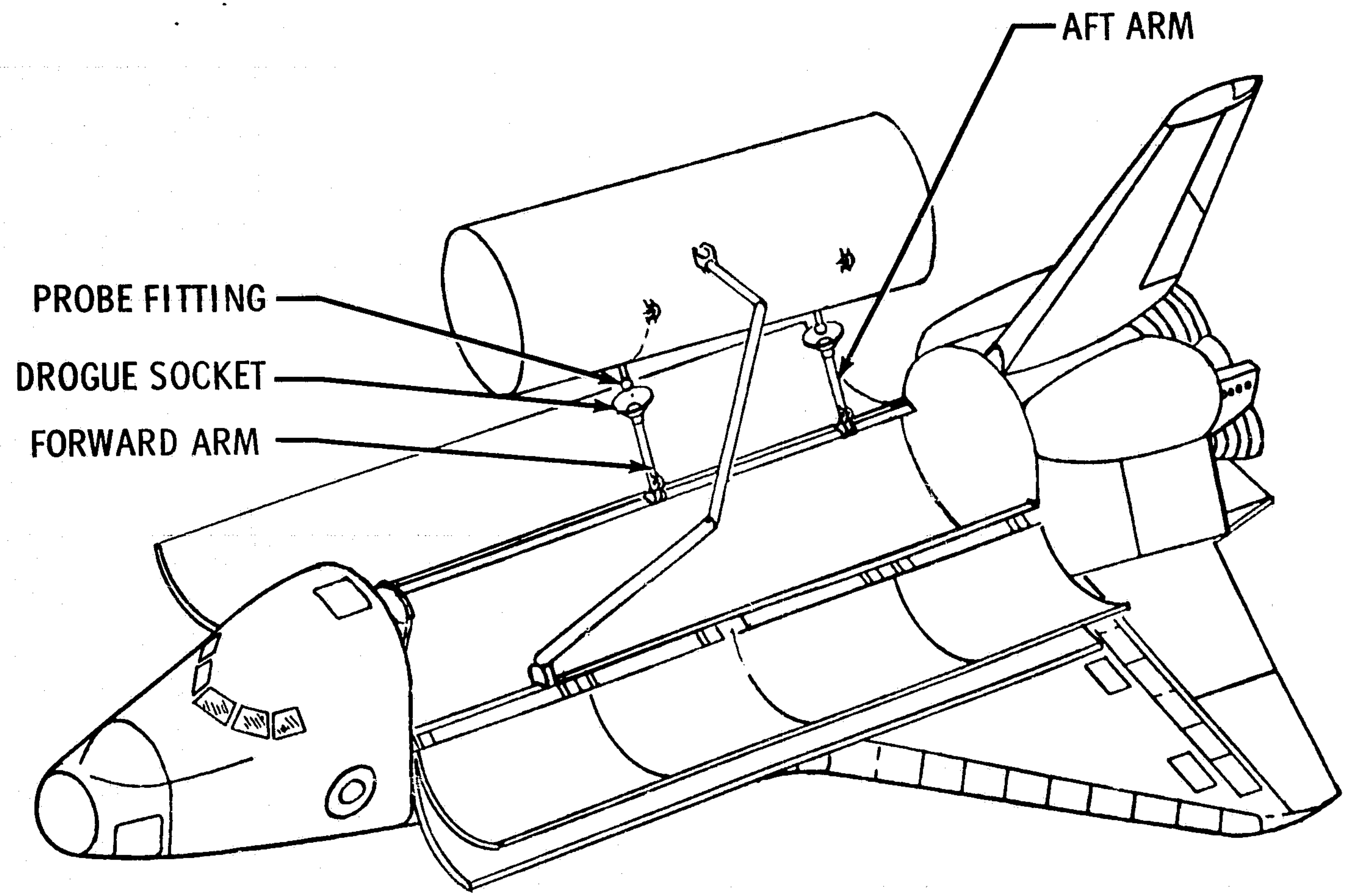
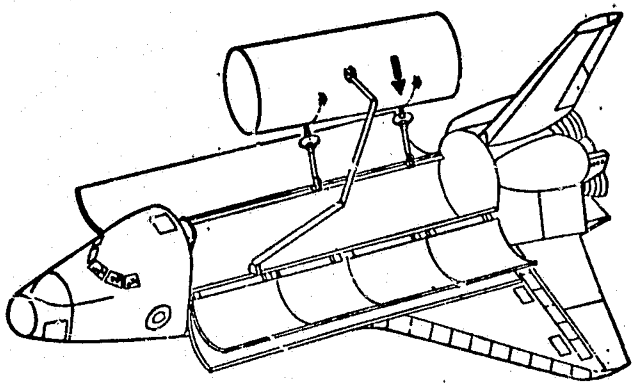
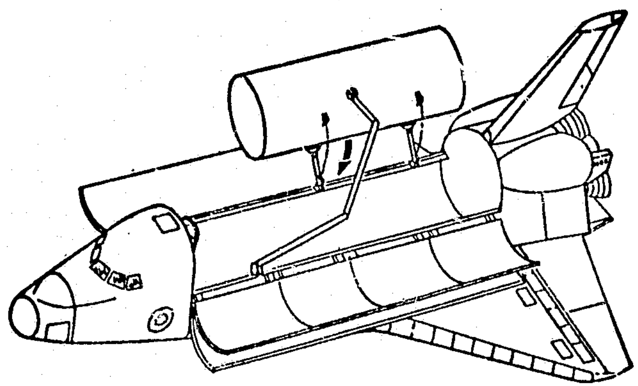


FIGURE 9-1

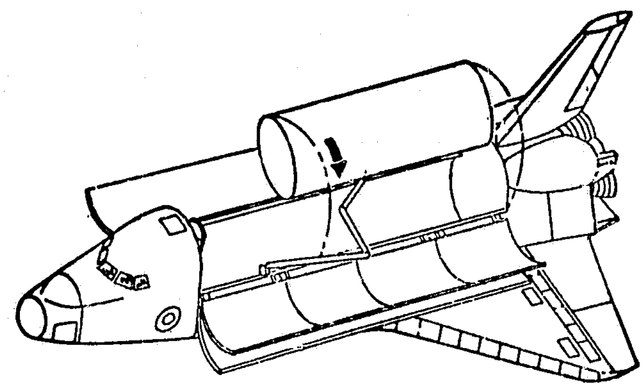
PAYLOAD INSTALLATION AND DEPLOYMENT AID CONCEPT OPERATIONAL SEQUENCE



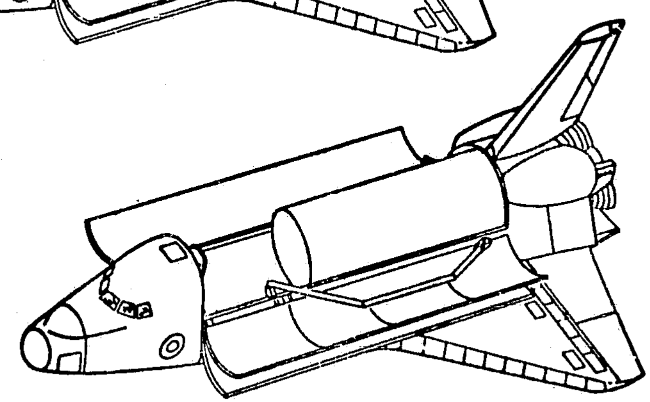
1
CAPTURE & ALIGNMENT
USING MANIPULATOR



2
ROLL ABOUT SOCKET PIVOT TO PICK
UP SECOND ATTACH POINT ON EACH ARM



3
MANIPULATOR RELEASE-
DRIVE ON ARM ROLLS
PAYLOAD INTO BAY



4
RETENTION FITTINGS LOCKED TO SECURE
PAYLOAD IN BAY (MANIPULATOR STOWED
OR POSITIONED FOR OTHER DUTIES)

FIGURE 9-2

PAYLOAD INSTALLATION AND DEPLOYMENT AID CONCEPT
STOWAGE SEQUENCE

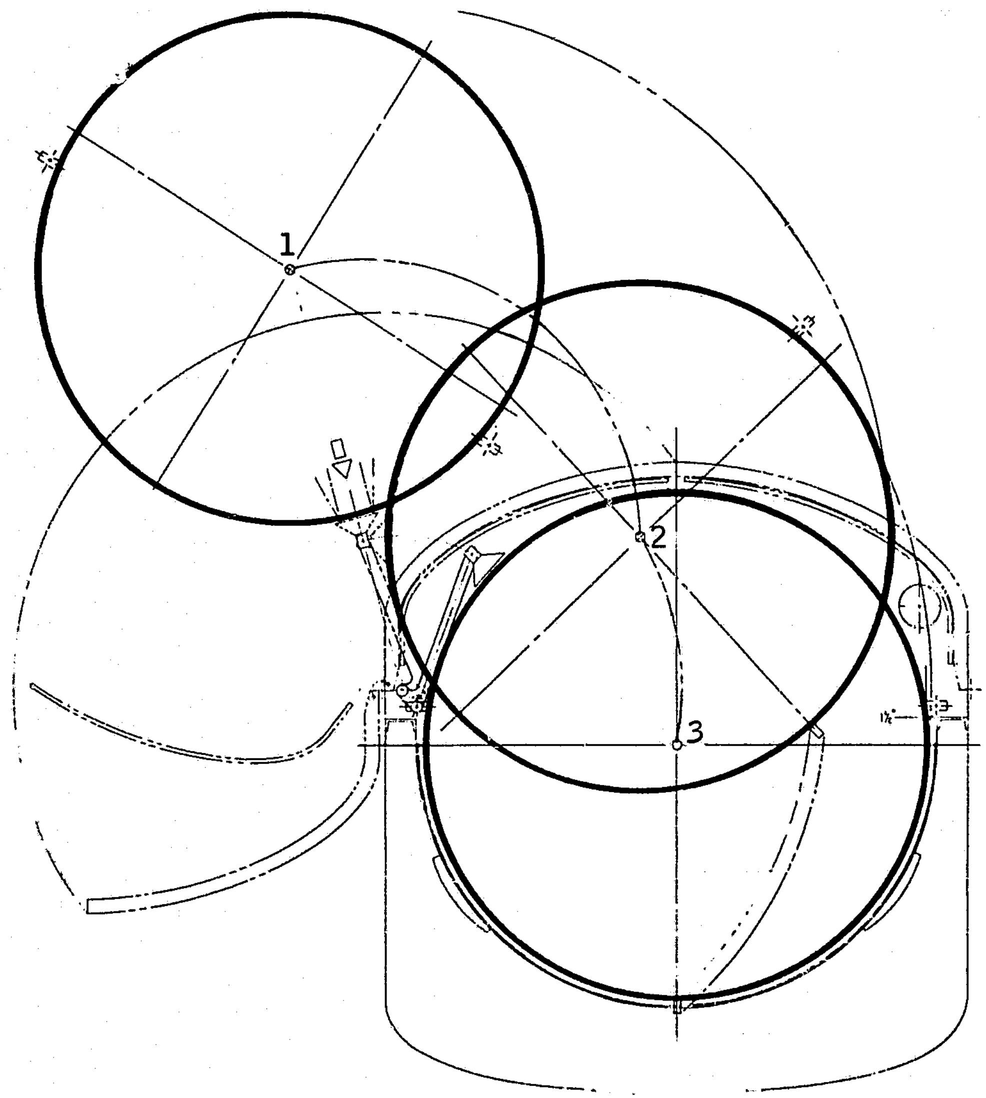


FIGURE 9-3

10.0 PAYLOAD RETENTION SYSTEM

The payload retention system shall be the structure and mechanisms that attaches the payload to the Orbiter on the pad, during all flight phases and landing operations. The system must accept relative deflections between the Orbiter and payload during pad installation, launch, on-orbit, payload deployment, payload retrieval, re-entry and landing.

There are 13 primary payload retention system locations on each sill longeron and at the keel for deployable payloads. These locations are described in JSC-07700, Volume XIV. These systems shall function on baselined vernier bridges for non-deployable payloads.

The payload retention system for a particular payload shall consist of a four-point determinate system: three longeron fittings (two primary and one stabilizing) and one keel fitting. Primary longeron fittings shall take X and Z loads only. The keel fitting shall take only Y loads. None of these fittings shall take moments in any plane.

Each retention system must accommodate Z motion of the payload trunnions for pad installation and post-landing removal. Arc motions of the payload trunnions particular to the payload installation and deployment aid concept for inflight deployment/retrieval of payloads must also be accommodated. All four trunnions will rotate about the longeron hinge into their respective retention fittings. There will be three separate arc motions because of the difference in trunnion distance from the center of rotation. With the PIDA longeron hinge installed on the right sill longeron, rotation on a large radius of the payload trunnion into the retention fitting on the left longeron is essentially the same as the Z motion of the payload trunnion at pad installation. A particular guide mechanism would most probably be adequate for both cases.

Trunnion arc motion (on a large arc) at the keel closely approximates rectilinear motion 50° off the Z axis. This motion will necessitate an active joint whereas the baselined keel fitting is passive. A redesigned keel bridge will be necessary.

Motion at the right longeron will be on a very short radius. This probably will be the most demanding of the three areas to be designed. However, the required guide capability of this fitting might possibly be less than the other three, particularly if the stabilizing fitting can be on the right longeron

11.0 MAN-MACHINE ENGINEERING

11.1 INTRODUCTION

This section summarizes man-machine engineering data collected and evaluated during the Manipulator Track Task simulations that were performed from late March through mid-May of 1975. The simulations were performed in support of defining specifications for the Shuttle Orbiter Remote Manipulator System (RMS). Three data sources were used: (1) comments made by the test subjects during simulations or during informal debriefings following the simulations; (2) an analysis of a series of photographs made of all test subjects during actual simulations; and (3) personal observations. The subjective comments were generally tempered by and reflect the subjects' understanding of the limitations inherent in the simulator (i.e., arm length, bay length, arm and payload [balloon] dynamics, et cetera).

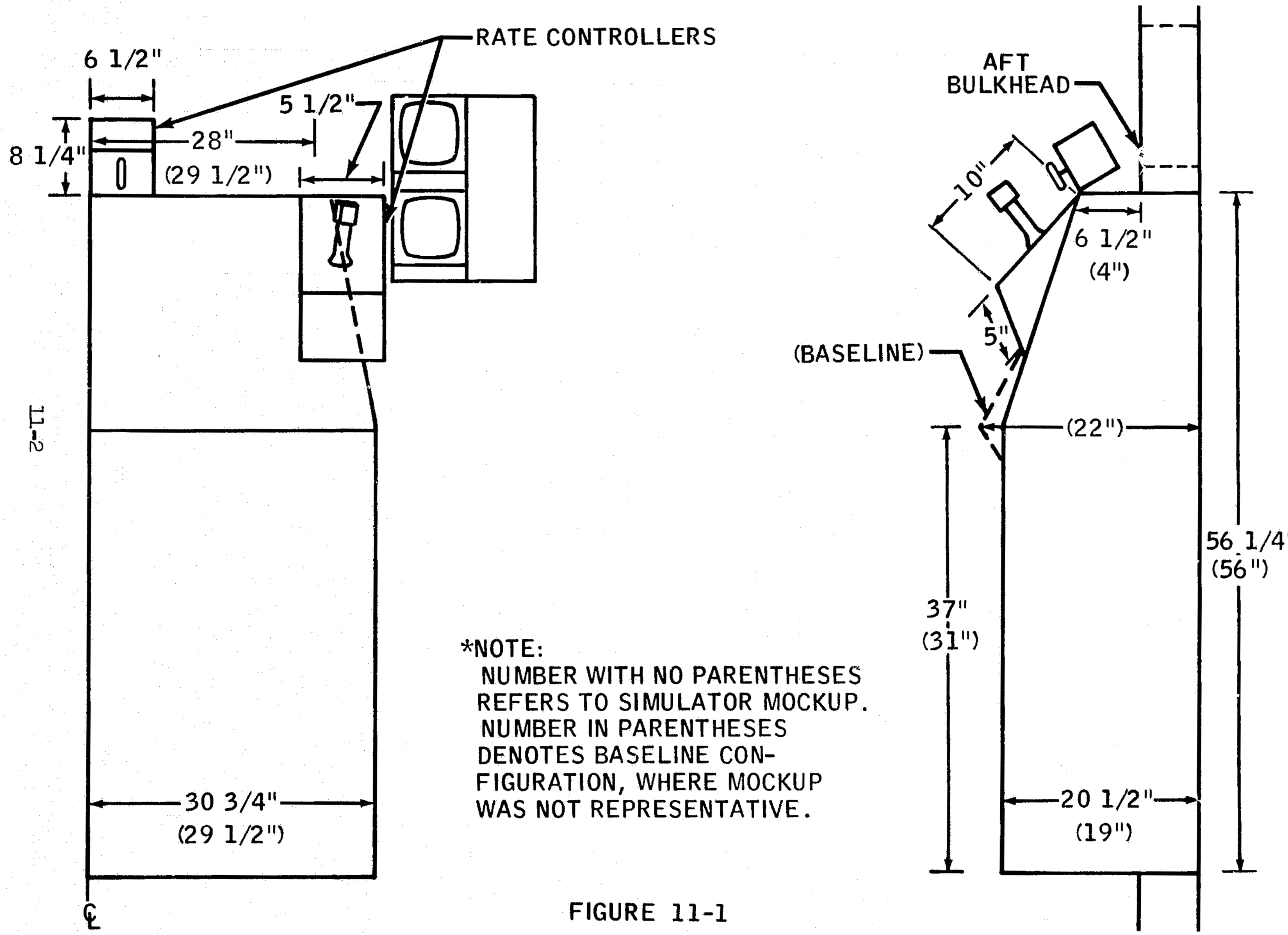
11.2 OPERATOR/WORKSTATION INTERFACE EVALUATION

One of the major concerns raised by the simulations was the operator/workstation physical interface. This interface includes design eye, operator posture, operator restraints, and workstation physical layout. The workstations utilized (representing the manipulator operator's station only) during the Track Task simulations are shown in Figures 11-1 through 11-3. The general workstation consisted of a control and display panel with geometry approximating the baselined version (see Figure 11-1 for comparison of mockup with baseline). The panel, shown close-up in Figure 11-2, included CAM 1400-peculiar computer interfaces, a CAM 1400 arm limit position indicator display, an arm controller sensitivity display for rate mode only, and TV camera controls. Rate controls were permanently mounted on the panel and disconnected when the replica controller was used. Two black and white 9-inch television monitors were positioned to approximate the baseline for operator viewing. TV monitor controls for brightness, contrast, et cetera were located directly under each monitor.

An overview of the workstation layout for the replica control mode is shown in Figure 11-3. The 1:20 scale controller is shown. The simulated Orbiter cabin included the two aft bulkhead windows and two overhead windows. The layout for the rate control mode appears in Figure 11-4. Two noteworthy items are evident: (1) mockup of ejection seat rails (discussed later in this section); and (2) wooden blocks on the floor, which were utilized by some subjects to raise their eye points by as much as 5 inches.

Six subjects performed several tasks with the manipulator. Various subject heights and techniques used for operating the manipulator indicate that a "design eye envelope" is more realistic to consider than specific design eye points. Subject movement ranged from very little to a large amount. The prime operator postures were: (1) standing erect, close to panel, looking out aft window (Figure 11-5); (2) leaning back without foot relocation, looking out overhead window (Figure 11-6); (3) standing erect,

RMS SIMULATOR WORKSTATION PANEL GEOMETRY



*NOTE:
NUMBER WITH NO PARENTHESES REFERS TO SIMULATOR MOCKUP. NUMBER IN PARENTHESES DENOTES BASELINE CONFIGURATION, WHERE MOCKUP WAS NOT REPRESENTATIVE.

FIGURE 11-1

NASA S 75 11116

RMS WORKSTATION

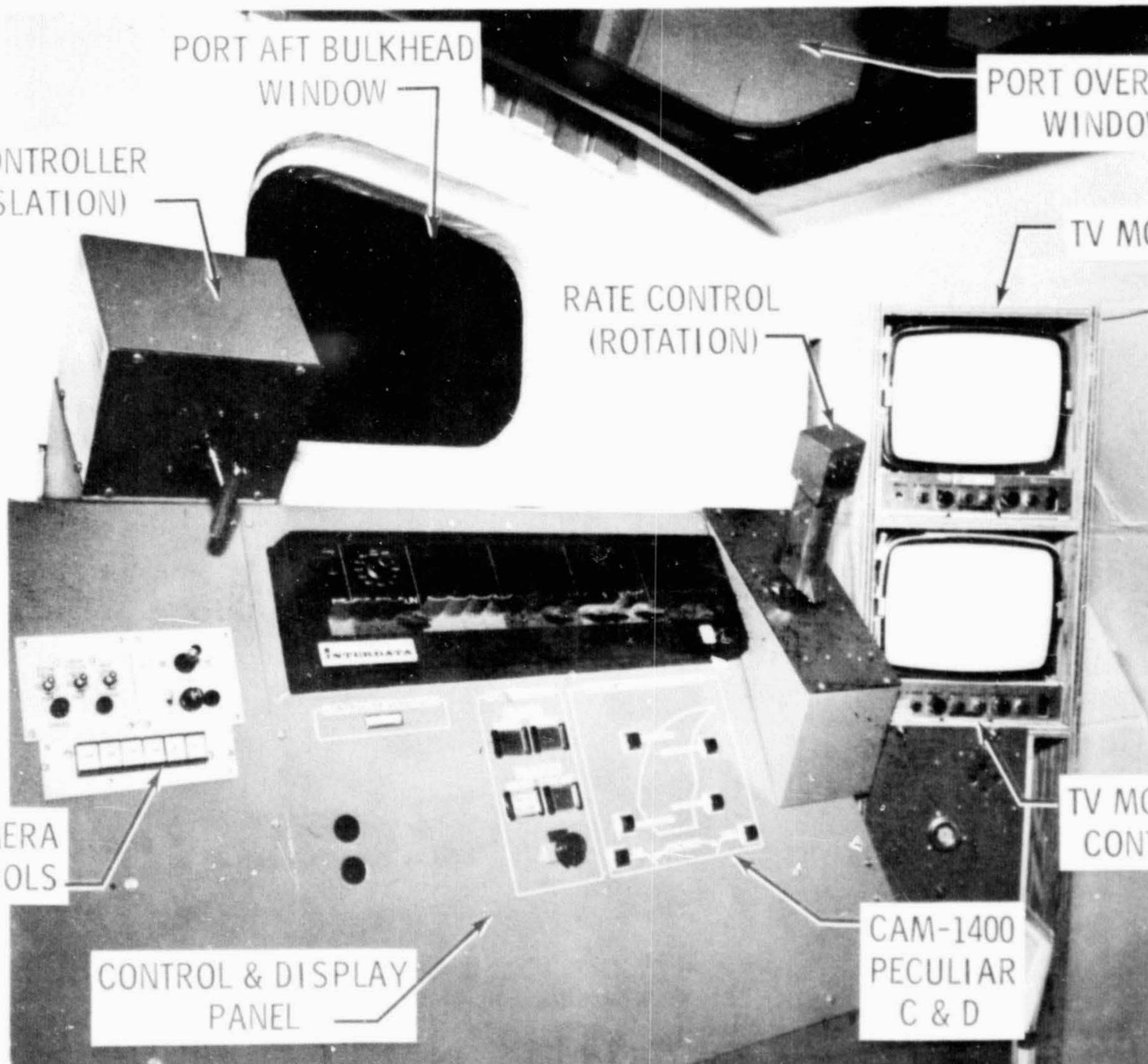


FIGURE 11-2

NASA S 75 11114

RMS WORKSTATION - REPLICA CONTROL MODE

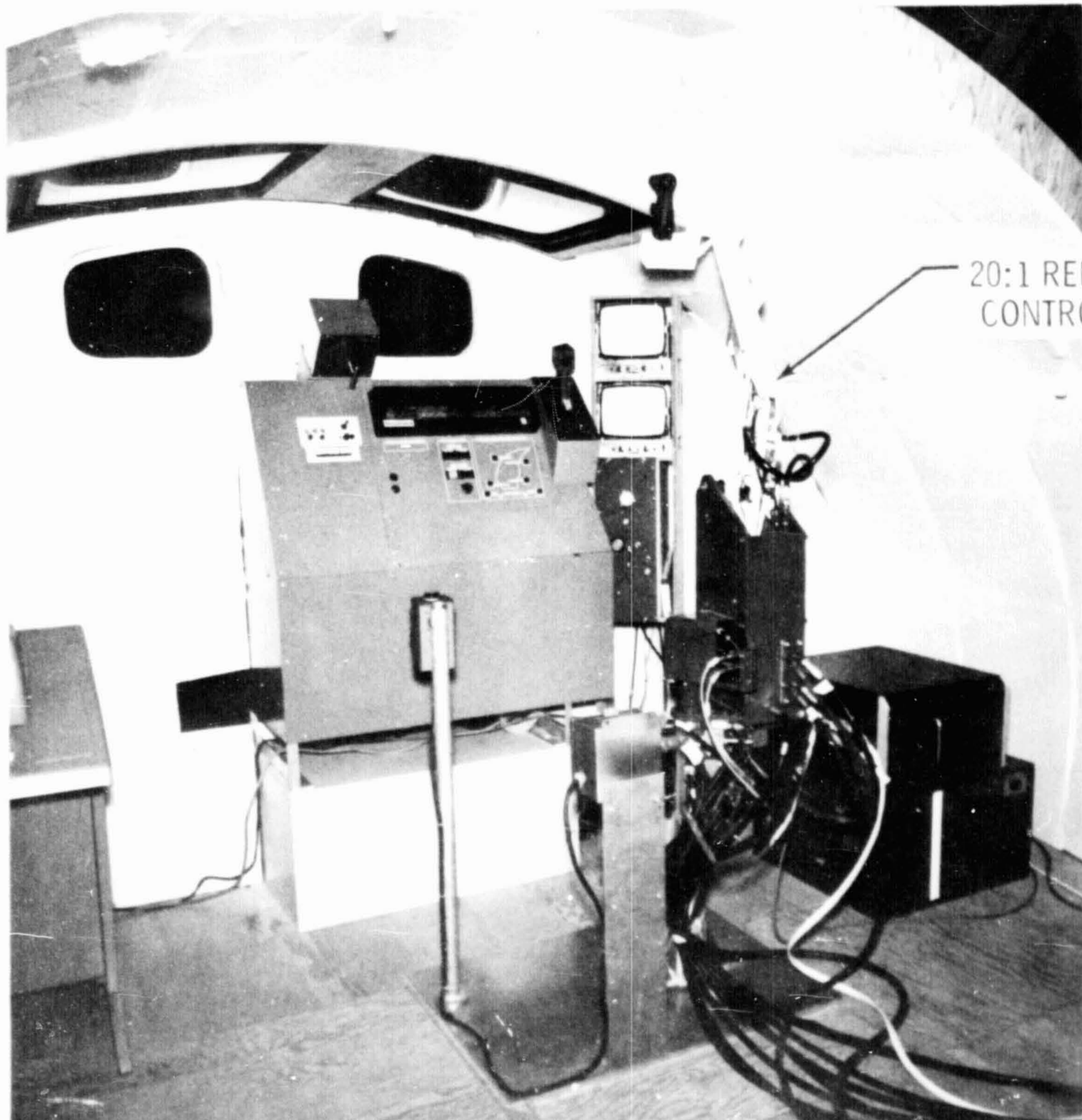


FIGURE 11-3

NASA S 75 11115

RMS WORKSTATION - RATE CONTROL MODE

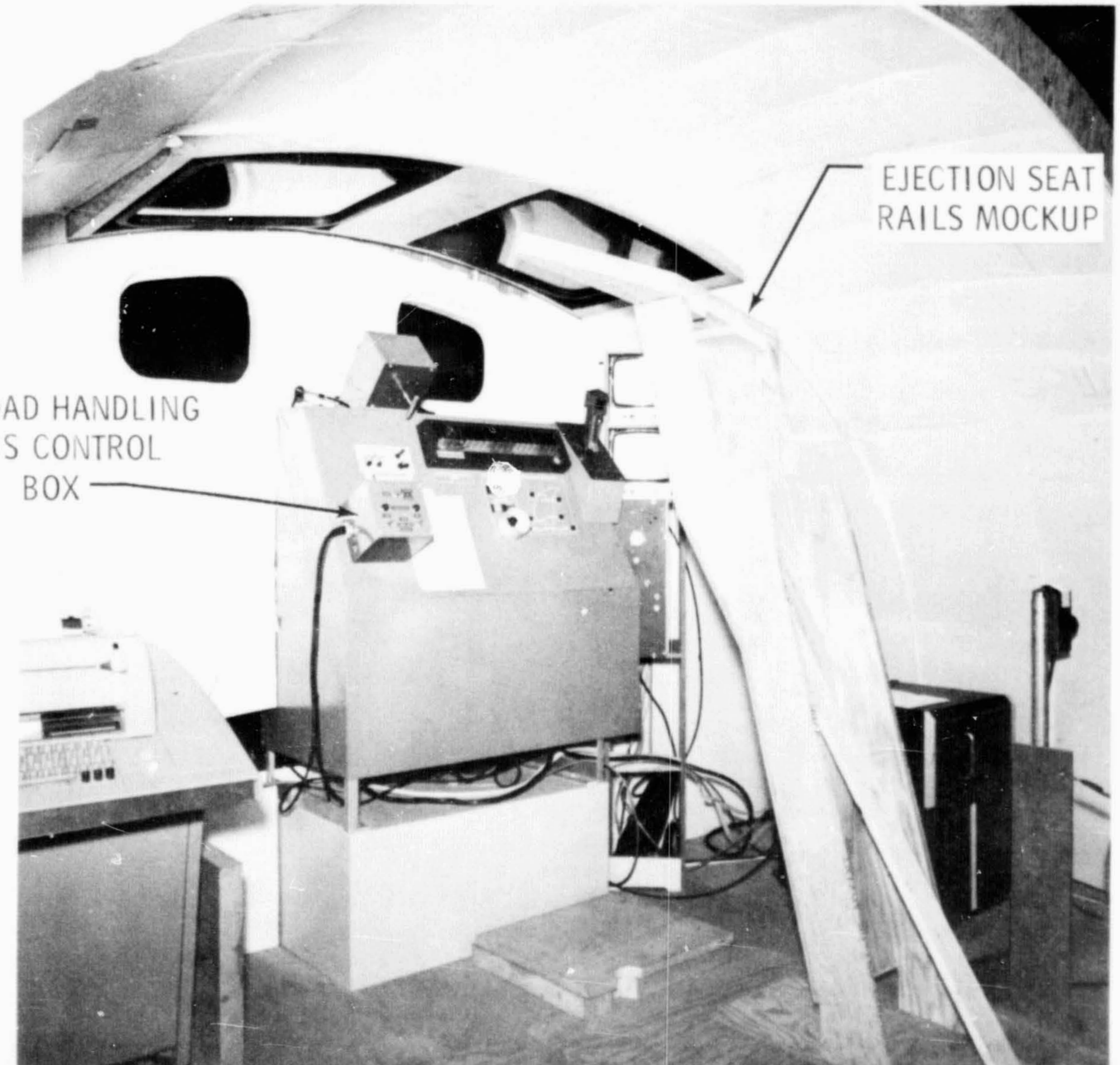


FIGURE 11-4

NASA S 75 11117

RATE CONTROL MODE - OPERATOR POSITION NO. 1

FIGURE 11-5

NASA S 75 11118

RATE CONTROL MODE - OPERATOR POSITION NO. 2

FIGURE 11-6

feet relocated, looking out overhead window (Figure 11-7); and (4) leaning forward, looking out aft window (Figure 11-8). The posture assumed was a function of the task being performed and the mix of direct and TV viewing. Leaning back in zero-g (as shown in Figure 11-6) will be easier than in one-g and may more realistically depict an in-flight occurrence than the posture shown in Figure 11-7 where the operator steps back. The posture in Figure 11-8 was more predominant when little use was made of the TV (i.e., the head was positioned closer to the window when long-term TV viewing was not required). Although all of these figures were "posed", the operator positions are representative of those noted in a series of photographs made during actual runs.

The variations noted above are compounded by two phenomena known to occur in a zero-g environment and should be treated accordingly. First, a height expansion of the human body occurs primarily due to the lack of a gravity field compressing the skeleton. A height increase of approximately two inches was noted for each of the Skylab 4 crewmen after three weeks in orbit. However, it is thought that this change occurs rapidly after first exposure to zero-g, probably within the first 24 hours, and thus raises the eye point.

Second, the human body exposed to zero-g tends to assume a natural, neutral posture. In this position, the eye height (i.e., from floor to eye level) is displaced downward from the one-g body erect posture by approximately five or six inches. The zero-g eye is approximately five or six inches lower than the one-g eye position. Also, because the neck naturally bends forward and causes the head to tilt downward, the zero-g natural line of sight is approximately 15° downward from the one-g horizontal line of sight.

The above observations and phenomena have application in at least three major areas associated with the RMS workstation: (1) in the layout of the control and display panel; (2) in the definition of the manipulator operator restraint system; and (3) in the identification of physical interferences between the operator and surrounding equipment.

Figure 11-9 illustrates an example of the layout problems. The subject uses the TV controls, presently placed at the center of the aft station where the controls are accessible by both crewmen. However, the TV image is at the right of the crewman. The desirability of placing the TV controls closer to the TV monitors for convenience is obvious and was voiced by several subjects; however, their comments also reflected the benefits of the central location for joint-control capabilities by either the manipulator operator or on-orbit pilot. Additionally, the optimum position for the rate controllers might be elsewhere on the control and display panel where the controllers will be closer to the neutral body hand position.

Figure 11-10 shows a comparison of various foot positions which occurred during the runs. As previously stated, some operators shifted foot position quite a lot while other operators rarely moved their feet. Also depicted in four of the views are the blocks which were used at the subject's option to raise the eye position. The blocks could be added in one inch increments to a maximum of five inches. Use of blocks along with the changing foot

NASA S 75 11119

RATE CONTROL MODE - OPERATOR POSITION NO. 3

FIGURE 11-7

NASA S 75 11120

RATE CONTROL MODE - OPERATOR POSITION NO. 4

FIGURE 11-8

NASA S 75 11013

WORKSTATION LAYOUT
TV SYSTEM CONTROLS

FIGURE 11-9

NASA S 75 11010

SUBJECT FOOT POSITIONS

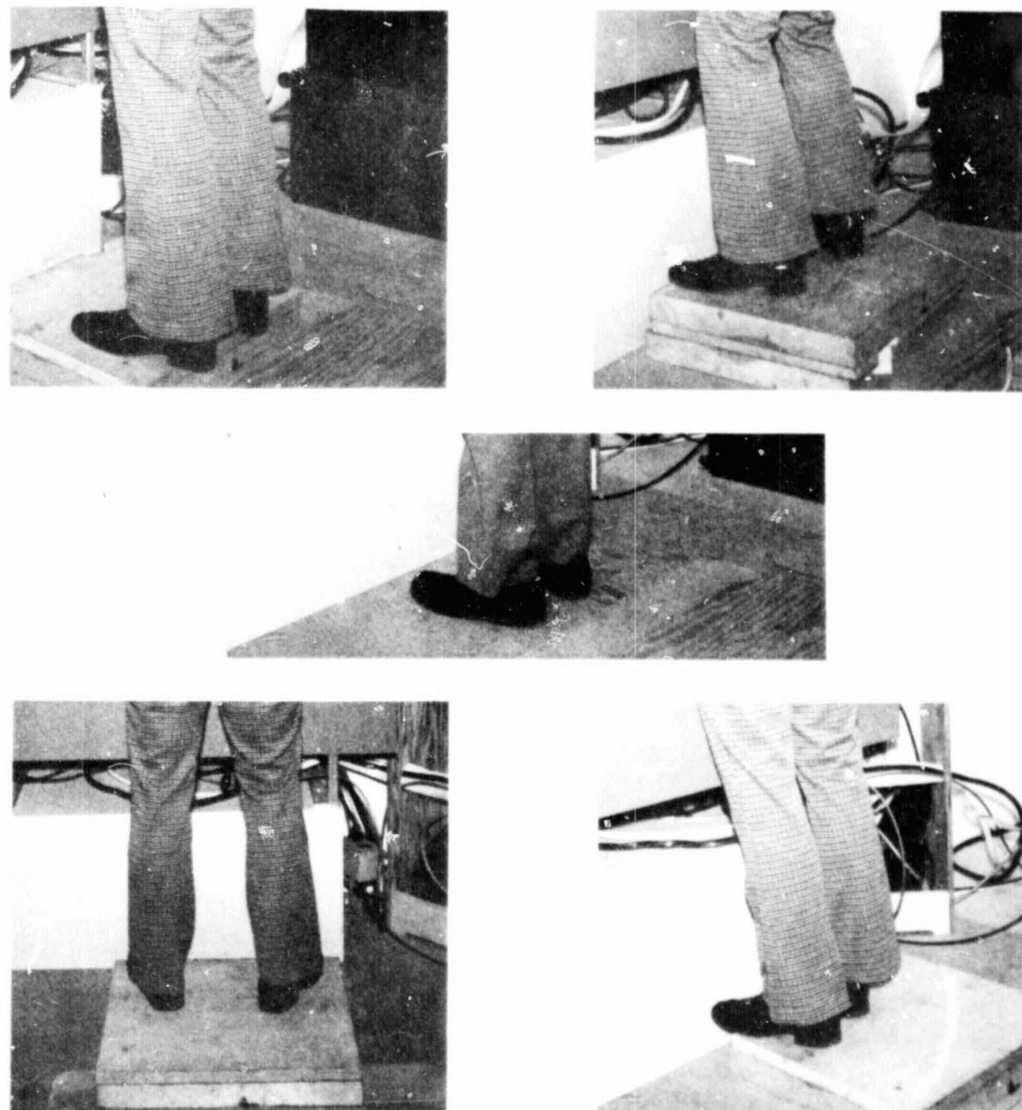


FIGURE 11-10

positions indicates the need for a restraint system that allows flexibility in both lateral and vertical foot displacement. Additionally, the neutral zero-g posture may dictate a sloping foot restraint (if foot restraints are selected) due to the natural angle at the ankle. Depending on the required controller force inputs, a restraint in addition to the foot restraints may be necessary (e.g., back or waist) to avoid operator fatigue. Inadvertent inputs made to the controllers when the operator leans back may dictate a need for handholds on the panel or around the window periphery. Finally, tilting the head upward for out-the-overhead-window viewing may also prove tiring for extended operations. Design of the restraint system should address these phenomena.

Figures 11-11 and 11-12 illustrate one example of the physical interference problems. The ejection seat rails will probably be present for flights during which the RMS will be used. The rails limit the flexibility of the operator to attain desired positions for viewing out the overhead window. They directly interfere with the desired head-tilted-back mode (Figure 11-11). Depending on operator height, the shorter operators may attain alternate postures for this mode (Figure 11-12). However, some bump protection (e.g., padding) on the ejection seat structure will be required.

11.3 OPERATOR VISUAL SUBSYSTEM EVALUATION

Another area of concern resulting from the simulations is the operator visual subsystem, including the following: (1) direct line of sight viewing; (2) TV use and viewing; (3) external cabin, payload bay lighting; and (4) other optical phenomena such as glare, operator visual capability, alignment aids. The following discussion data is based on subjective data and reflects an interpretation of operator comments combined with the author's personal observations.

Direct line of sight viewing was the mode preferable to the subjects. One subject summarized the group's feelings: "There's just no substitute for direct vision." Although the cabin structure prohibited complete visual coverage of the exterior, operators would reposition themselves as required to see the task directly. It should be noted that most of these simulations were made with ambient lighting (i.e., Building 9A bay lights on) in excess of 50 foot-candles. Line-of-sight viewing occurred through both aft and overhead windows. Also, because of the simulator layout, tasks were generally within a 30 foot radius of the operator. Evaluations of direct viewing for tasks 30 to 60 feet from the operator and with lower light levels are required.

When the manipulator arm position prevented direct viewing of the end effector, the operator was presented with a problem of determining the correct control input to obtain the desired movement or reaction. Operator solutions to this problem ranged from trial and error to "body english" by using his own arm to simulate the RMS arm position. The use of TV cameras supported this activity. Nevertheless, an arm position display of some sort is indicated for further evaluation and should facilitate this activity.

NASA S 75 11011

EJECTION SEAT RAIL INTERFERENCE

FIGURE 11-11

NASA S 75 11012

INTERFERENCE WORK-AROUND

FIGURE 11-12

The use of a scale model or a generated, 3-D perspective scene of the Orbiter/arm/payload bay/payload was suggested. Further study is required of those tasks which require mental transformations of axes to identify the correct input, particularly those activities that require the crewman to operate in a posture of leaning back and looking out the overhead window.

The use of the television system seemed to be a function of the task being performed and was dependent in part on whether satisfactory direct viewing was available. At least two simultaneous TV camera views were required for the majority of tasks. For some situations three camera views were simultaneously used. Split screen viewing of two cameras on one monitor was extremely useful. Some split screen capability appears to be extremely beneficial, if not required, as a means to compare different views on one screen or for providing a perspective relationship of more views simultaneously.

Use of pan, tilt, zoom and other camera adjustments also seemed dependent on the task being performed. However, inclusion of these capabilities on all payload bay cameras, including the arm-mounted camera, will provide flexibility to support and enhance RMS operations over a wide range of tasks. Monitor adjustments were also utilized and their placement appears satisfactory.

A variety of TV camera locations in the payload bay were examined. Operator use of the cameras indicated the following:

a. For one task requiring two simultaneous views down the longerons, locating both cameras pointing aft was preferable to one pointing aft and one forward. However, the camera located at the aft end was utilized for another task requiring viewing from that direction.

b. The keel camera, which would have major utilization in stowing a large payload, was judged as not too useful. However, the usefulness of this camera location could not be adequately evaluated because the simulator geometry prevented centering the payload over the bay at the desired height to be lowered straight down. A longer arm would permit this evaluation.

c. The perspective view of the cameras mounted on the longerons should be directly down the longeron. Positioning the camera either inboard or outboard of this line gives misleading cues to the operator.

d. Use of a tail- or extendible boom-mounted camera to display a bird's eye view of the Orbiter/RMS/payload bay/payload appears desirable and should be evaluated.

e. Because the camera selected for use was primarily a function of task being performed, a TV system within the payload bay that is flexible in camera positions within the bay area (i.e., ground-reconfigurable for specific payload/mission) would provide optimum support for a maximum of payloads.

A complete evaluation of payload bay lighting was not feasible for all tasks. However, some evaluations were made with Building 9A lights off. In this mode, with payload bay lights on, light levels were slightly less than 20 foot-candles but some of this light was from building night lights and an office adjacent to the test area. Simulation evaluations were minimal but there were two suggestions which are: (1) if the arm-mounted camera does pan/tilt, the arm-mounted light should pan/tilt concurrently; and, (2) for supplementary lighting, evaluate a light mounted on each payload bay camera.

Other problems were not evaluated during the Track Task and are currently open for controlled investigations. The problems are: (1) glare problems due to reflections from the H film-insulated radiator on the payload bay doors and from various payload reflective surfaces; (2) interference from glare and reflections from interior cabin lights and cockpit displays on aft and overhead window panes; (3) visual capabilities of the operator to perform tasks when viewing the work area at greater distances (i.e., 30 to 60 feet) under various illumination conditions (solar illumination to nighttime extremes) and relative motions; and (4) visual aids, marks, et cetera on payloads, the payload bay, et cetera to facilitate RMS operations. Special attention must be paid to those on-orbit activities that operationally dictate that the sun is in the operator's field of view while using the RMS or, because of sun angle, require special crewman protection from glare.

11.4 SUMMARY

The following man-machine engineering conclusions have been made after observation of the Track Task simulations:

a. Various tasks and operator heights dictate a restraint system that is flexible in both lateral and vertical directions.

b. Crewman bump protection (e.g., padding) on appropriate portions of the back of the port ejection seat rail structure is mandatory.

c. At least in the forward half of the payload bay, direct viewing of the end effector contributes greatly toward effective and efficient manipulator operations.

d. Pan, tilt, and zoom capabilities should be included on all payload bay TV cameras, including the manipulator arm camera.

e. TV cameras are required to augment direct vision for payload handling operations.

12.0 CREW STATION REQUIREMENTS

12.1 GENERAL RMS REQUIREMENTS

The RMS shall be operated by a single crewman. Orbiter vehicle maneuvers or operations associated with RMS operations shall be performed by other crewmen. The RMS shall include features that will allow effective crew participation in the operation of the system. The RMS operator shall have the capability to direct the control of the RMS throughout all operational modes. Status of RMS subsystems shall be displayed for crew monitoring such as failure detection, mode of operation, mode selected, subsystems status, arm configuration, sequences, payload/manipulator interface configuration. Crew monitoring of automatic features with provisions for exercising command control is required. This includes the capability for crew initiation and determination of all crew safety control paths. Automatic systems shall be employed for manipulator operations only when required to obtain necessary precision or speed, or to relieve the crew of excessively tedious tasks. A manual override capability will be provided for all automatic control modes.

The RMS operator's station shall be designed for use and operation by a shirt-sleeve crewmember. The manipulator assembly shall be designed to support rescue EVA operations by crewmen equipped with self-contained EVA support systems.

The RMS shall be designed to permit efficient use of human capabilities. The information, principles and requirements contained elsewhere within this specification, in SC-D-0001, SC-L-0002, SC-M-0003, SC-A-0004, SC-C-0005, SC-D-0007, SC-C-0009, SC-E-0010, and in MIL-STD-1472, shall be applied to the design and development of the RMS and its associated GSE.

RMS design requirements shall include proper allocation of tasks between the RMS operator and automatic features of the system according to each one's capability for performing the required function. Design direction shall reflect human engineering requirements and principles in establishing the information needed by flight personnel for performing their assigned tasks and the preferred method of presentation of information, in optimization of design arrangement and layout of workplaces, consoles, controls and displays, and in environmental and personnel safety considerations.

12.2 CREW SYSTEM/CREW PROVISIONS (CS/CPS)

The CS/CPS shall provide those equipments and their arrangements to support the RMS operator in the performance of his duties during nominal and contingency operations. The requirements as stated herein include cabin arrangement, equipment requirements and crew physiological criteria requirements. The environmental criteria and requirements contained in Orbiter CEI Specification MJ070-0001 shall be utilized for the design of the RMS.

12.2.1 Cabin Arrangement

The cabin arrangement shall provide for effective performance of RMS tasks.

a. Flight Station - The flight stations shall reflect the command and control responsibilities of the RMS operator and provide for active management of the RMS subsystems. The categories and sequence of operator tasks shall be reflected in the display and control arrangements.

b. Visibility - External visibility from the flight station shall be provided by the aft and overhead crew station windows. The CCTV shall be used to supplement out-the-window vision.

c. Geometry - Crew station geometry shall accommodate the required range of crew sizes with respect to reach, body clearance, visibility, and mobility. The RMS station shall be located on the port side of the aft flight deck bulkhead where the operator can have direct out-the-window vision along both the -X and -Z axes.

12.2.2 Equipment Requirements

a. Crew Restraint - Crew restraints shall be provided to protect the RMS operator and allow performance of all tasks associated with nominal and contingency operations. The crew shall be restrained during the zero-g and RCS powered portions of the flight profile as required to supply the necessary reaction forces. The crew restraints shall contribute a minimum interference with the operation of and access to the controls and displays and shall not limit window utilization. The restraints shall be fully compatible with 5 to 95 percentile crewmembers for the performance of the RMS tasks. The requirements for EVA/IVA support equipment which are contained within SC-E-0006 shall be implemented.

b. Windows - Parallax, distortions, and unwanted reflection from glass (both window and instrument cover) and similar surfaces shall be kept to a minimum. Anti-reflection coatings on glass surfaces shall be used in order to reduce reflection.

Consideration shall be given to the use of window filters in order to reduce sun shafting. When not in use, these filters shall be retractable from the window area.

12.2.3 Interior Lighting

Interior lighting shall provide for control and display panel illumination. It shall be adjustable in intensity to compensate for varying ambient light conditions and also to insure retention of crew visual adaptation. A primary and secondary means of control and display panel illumination shall be provided. The primary means shall be integral with the controls and displays. Lighting shall also be provided for crew use in illuminating remote or shadowed areas of the crew cabin.

12.2.4 Marking and Identification

Interior and exterior marking, coloring and identification, including nomenclature shall be provided as required to support the performance of tasks by flight and ground servicing personnel. The requirements contained within SC-D-0001, SC-L-0002, SC-M-0003, SC-A-0004, SC-C-0005, SC-D-0007, and SC-C-0009 are applicable.

12.2.5 Display and Control Panels

Display panels, control panels, and consoles shall be provided for the crew stations incorporating a design goal to permit maximum viewing and operation of displays and controls (D&C) by the RMS operator. The panel surfaces shall be consistent with the crew station geometry and be compatible with viewing and reaching requirements. The control panel placement and layout shall be compatible with the reach and vision capabilities of a crewman standing in a zero-g erect position with the restraint system being utilized.

a. Accessibility - D&C equipment and devices shall be mounted so as to facilitate access for maintenance. Installations which require sequential removal of assemblies shall be avoided. Wherever possible, devices shall be so mounted that an individual device is removeable from the panel without electrical or mechanical removal of other functional elements. Means shall be provided to obtain access to volumes behind panels without electrical demate of equipment on the panels.

b. Connector and Wire Harness Verification - Displays and controls equipment design shall allow visual verification of interface connector mating and wire harness condition during installation in the vehicle.

c. Modular Design - The RMS D&C shall be of a modular design so that it can be installed/removed from the Orbiter as required for a given mission. The D&C panels shall be compatible with the Orbiter aft flight deck equipment racks and the MIL-STD-189 size and mounting provisions being used. The D&C for the RMS itself shall be located on a panel separate from the D&C for the television and payload bay lighting so that operation of the latter systems can be retained for missions on which the RMS is not required. The D&C shall be designed to fit in the smallest standard panel possible, but in any case the RMS D&C shall fit in a panel no larger than size R.

12.2.6 Inflight Data Requirements

Data and information will be supplied by the RMS contractor for inclusion into the GFE inflight data references to be utilized by the crew.

12.2.7 Extravehicular Transfer

Aids will be provided for extravehicular crew transverses via the manipulator arm assembly. Provisions shall be included to accommodate EVA crew and equipment transfer to and from other orbiting vehicles and between external Orbiter areas.

12.2.8 Crew Physiological Criteria & Operational Requirements

The RMS shall be designed to accommodate the crew physiological criteria and operational requirements contained within Orbiter CEI Specification MJ070-0001. Flight station RMS equipment and interfaces shall be designed for operation by a shirt-sleeve crewman.

12.3 DISPLAYS AND CONTROLS SUBSYSTEM (D&C)

The RMS Displays and Controls Subsystem shall consist of all those devices in the crew compartment, which enable the RMS operator to control, monitor and/or observe relevant aspects of RMS operation and performance. The display and control function shall be required for RMS operation if the information or control action input provided by such function is essential and in sufficient depth to allow an RMS operator decision or action needed to successfully complete RMS/payload operations under normal conditions, or to return the RMS to a safe configuration under emergency conditions. The display and control functions provided by the D&C equipment shall give the RMS operator sufficient depth of information and command access to the spacecraft systems to enable the crewman to successfully accomplish the following operations during the mission:

a. Effect manual RMS operation as required under normal mission conditions or contingency operations

b. Safe shutdown of the RMS

c. Monitor of the RMS as required for normal mission or contingency operations

d. Recognize malfunctions or incipient hazards to crew, vehicle, or mission in operating the RMS, and effect adjustment or selection of alternate subsystem elements as provided; or effect mission change if normal subsystem operation cannot be restored by any of the above actions and effect monitoring of RMS subsystem condition for normal or contingency operations.

12.3.1 Subsystem Requirements

It is required that the D&C equipment as defined herein present information to, and accommodate control action inputs from, the RMS operator for the following purposes:

Initiation and monitor and control of RMS maneuvers, maneuver sequences, and event sequences

Operation of RMS subsystems and management of subsystem conditions

Management of RMS energy sources

Alarm for hazardous conditions and RMS subsystem malfunctions affecting the mission

a. Design Requirements - The design of controls and displays shall conform to the requirements delineated within SC-D-0001, SC-L-0002, SC-M-0003, SC-A-0004, SC-C-0005, and SC-D-0007.

b. Subsystem Equipment Location - The general layout and arrangement of RMS and RMS-related displays and control equipment shall be as shown on Figures 12-1 and 12-2. Figures 12-3, 12-4 and 12-5 illustrate conceptual D&C panel arrangements that employ dedicated D&C and are intended for guideline information only.

c. Subsystem Components - The displays and controls equipment shall consist of GFE and CFE sub-assemblies and other items together with provisions for installation and operation of these items. The displays and controls equipment shall provide displays and controls for RMS operation, RMS subsystem management and general crew usage as defined by the listed operational subsystems.

(1) Subsystem: Arm Guidance and Control - D&C shall be provided to select and indicate any one of the following control modes:

Automatic preprogrammed control

Manual augmented control

Backup direct drive control

The controls associated with each control mode shall be enabled only when that particular mode has been selected.

The automatic and manual augmented control modes shall be capable of operating in any one of three coordinate systems as determined by crew selection: end effector referenced, Orbiter referenced, or payload referenced. Crew selection for either of two rate limit modes shall also be provided.

(a) Automatic Control - D&C shall be provided to individually select, start, and stop preprogrammed manipulator routines. Indication of the routine selected, that the program is running, and that the routine has stopped shall be provided.

(b) Manual (Augmented) Control - Manual control of the manipulator arm has been baselined as a two-handed operation that shall direct the terminal end of the arm without conscious effort to control the individual joints. The input devices shall be two 3-degree of freedom (DOF) displacement type handcontrollers, which shall be capable of commanding resolved rates for the six DOF of the arm. An attitude controller shall allow roll, pitch, and yaw control of the end effector. A translation controller shall provide up/down, left/right, in/out translation of the end effector.

The RMS controllers shall provide outputs proportional to grip deflection. The attitude controller shall be designed and mounted for right hand operations and the translation controller for left hand operation. The placement of the controllers shall allow viewing out the window and of the CCTV monitors, and shall correspond to the relative pilot axes so that the required

CONCEPTUAL DISPLAYS AND CONTROLS PANEL ARRANGEMENT

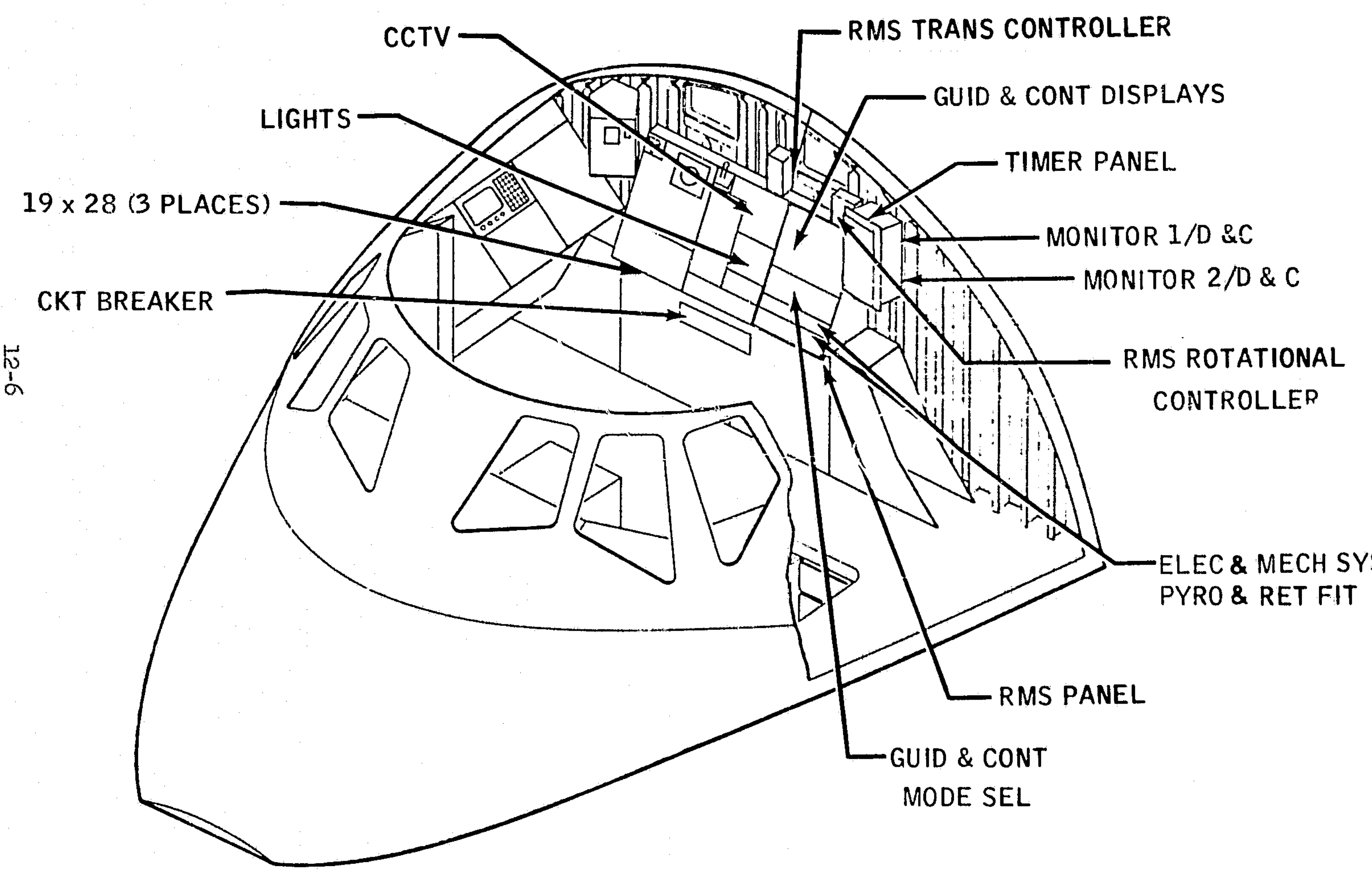


FIGURE 12-1

CONCEPTUAL DISPLAYS AND CONTROLS PANEL DETAIL ARRANGEMENT

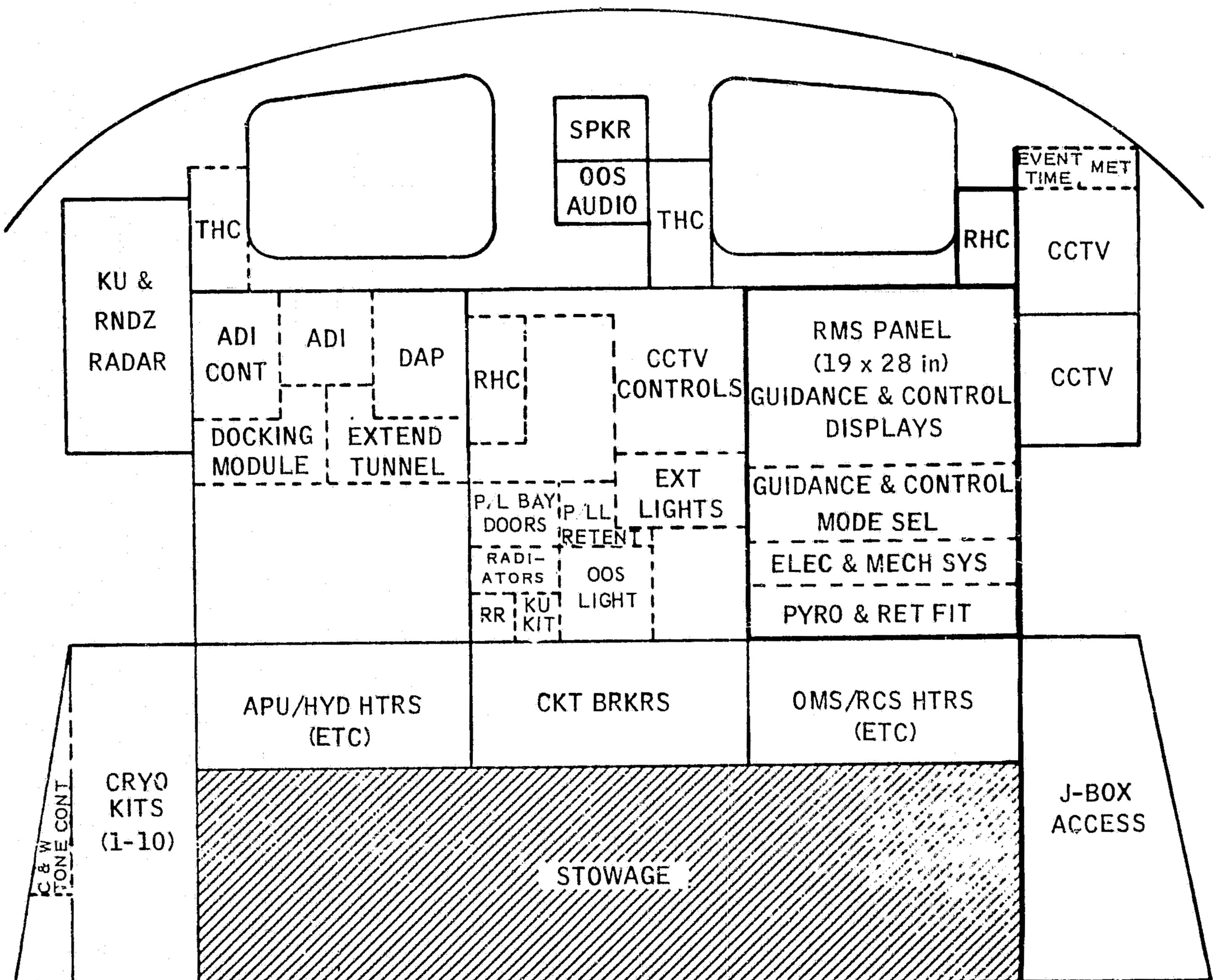


FIGURE 12-2

RMS RIGHT HAND PANEL CONCEPTUAL ARRANGEMENT

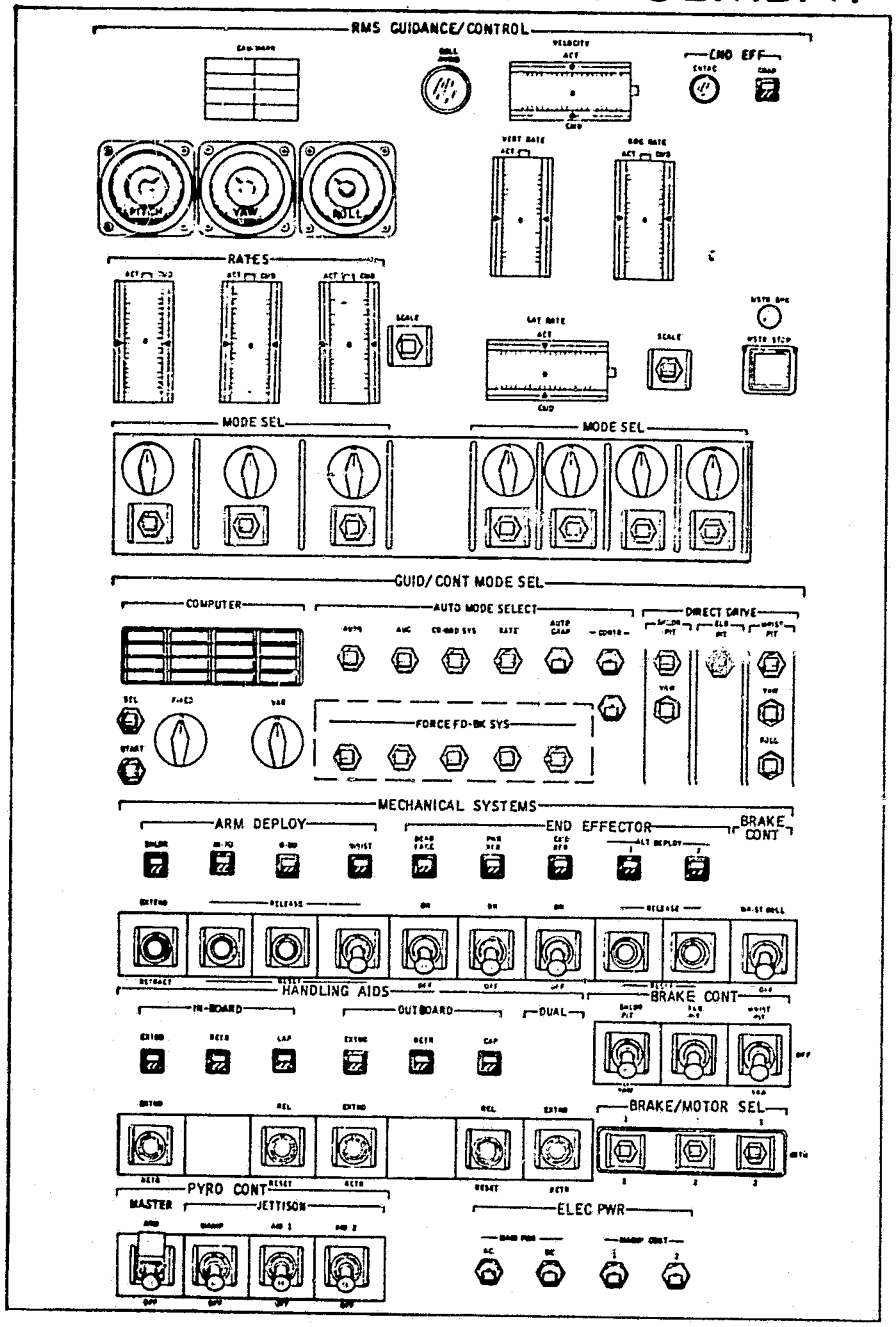
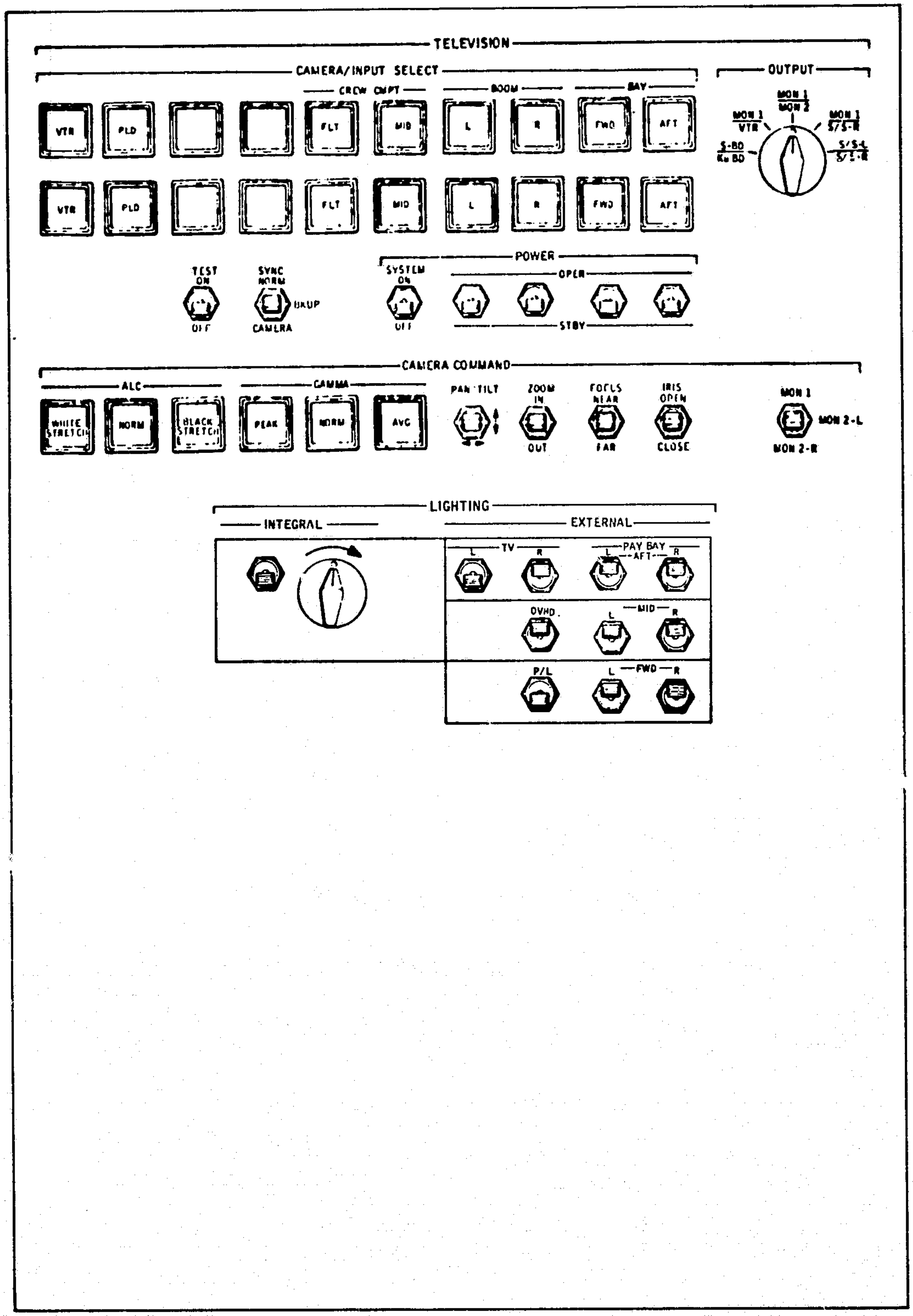


FIGURE 12-3

RMS MID-PANEL-CONCEPTUAL ARRANGEMENT



C-2

FIGURE 12-4

RMS CREW STATION
CONCEPTUAL TV MONITOR ARRANGEMENT

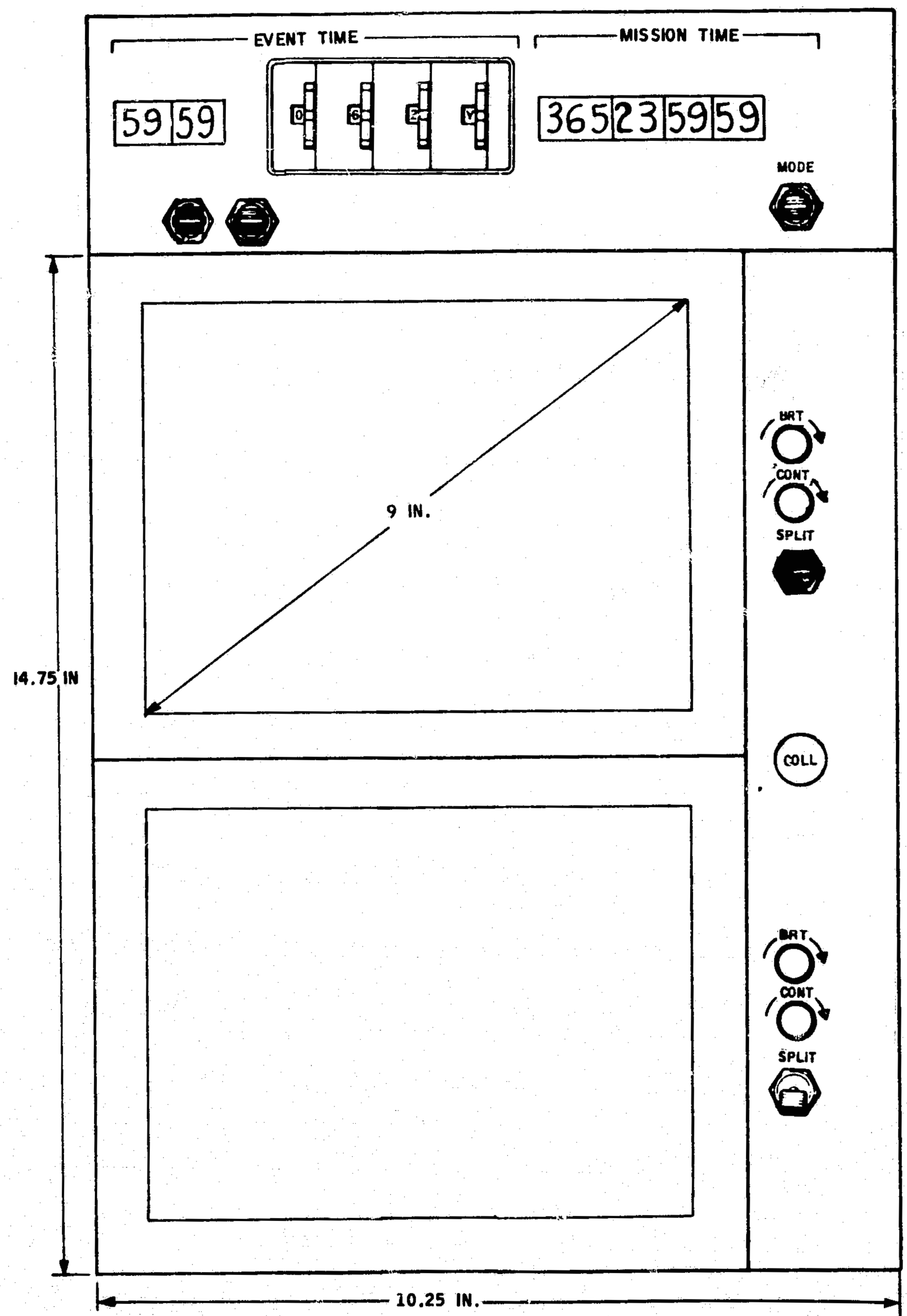


FIGURE 12-5

input motions are obvious and not subject to the operator ability to perform coordinate transformations. It shall be possible to make inputs into each axis separately or into multiple axes simultaneously. However, each controller axis shall be independent so that the input motions, force feel, and electrical outputs are distinct and have no effect on another axis.

(c) Direct Drive Control - A switch shall be provided for each joint motion to allow for the slewing of the arm in a direct drive control mode, which shall be independent of any computer functions.

(d) End Effector Control - A switch shall be provided on the grip of the RMS attitude controller to open or close the end effector. D&C shall also be provided to control and monitor primary and alternate end effector interfaces.

(e) Displays - The arm guidance and control display system shall present relative state vector information between the arm, its components, the Orbiter, and payloads. The system shall be capable of displaying information referenced to any one of three coordinate systems with crew selectability. Coordinate systems are end effector referenced, Orbiter referenced, and payload referenced. The presented information shall be in sufficient depth and format to minimize the workload of the RMS operator in both the automatic and manual control modes. If required the display system shall help compensate for control system lags and nonlinear responses by presenting information in an actual and command or predictive format. The operator shall be provided with a positive indication that automatic/manual commands have been generated and are being processed with the intent of monitoring system performance and preventing unnecessary subsequent inputs into the control system. The following information shall be presented to the RMS operator:

Angular displacement - Simultaneous analog presentation of arm, shoulder, elbow, and wrist angular displacements (pitch, yaw, and roll) for the purpose of performance monitoring and steering of the arm in the manual modes

Angular/translational rates - Simultaneous analog presentation of joint and end effector angular and translational rates for the purpose of performance monitoring of arm response in the automatic and manual control modes

Tip Velocity - Analog presentation of end effector tip velocity magnitude for performance monitoring of automatic/manual operations involving large or sensitive payloads

Event/Mission Time - Individual digital display of event and mission times for monitoring of automatic/manual sequences and general time referencing. Orbiter furnished displays shall be used for this purpose.

(2) Subsystem: Mechanical Systems - D&C shall be provided to control and monitor the operation of the manipulator arm deployment system, end effector interfaces, handling aids system, and brake control system.

(a) Manipulator Arm Deployment - Extend/retract and lock/release control switches shall be provided for arm deployment and arm hold-down, respectively. Status indicators shall be provided to indicate that the arm has been fully extended (deployed) or retracted and that the arm hold-downs are locked or released.

(b) End Effector Interfaces - D&C shall be provided to control and monitor electrical and mechanical interfaces of primary and alternate end effectors. Control switches and status indicators shall be provided for deadfacing end effector signal/power paths, for signal/power transfer between alternate end effectors, for the capture/release of end effectors, and to lock or release each end effector (primary and alternate) from its installed or stowed location. An indication of end effector contact and grapple status shall also be provided. End effector command control requirements are specified in 12.3.1.

(c) Handing Aids - Extend/retract switches and capture device lock/release switches shall be provided for individual and collective control of payload handling aids. Status indicators shall be provided for each aid to indicate that the aid has been fully retracted or released and if the payload has been captured or released.

(d) Brake Control - Control switches shall be provided for individual and collective control of manipulator arm motor brakes. The capability shall exist to manually command the brake systems. A positive means shall be provided to detect and compensate for electrical or mechanical brake failures.

(3) Subsystem: Pyrotechnic System - D&C shall be provided to jettison the manipulator arm(s) and handling aids in the event that they cannot be successfully stowed and locked down. The following D&C shall be provided: a master arm switch to arm or safe all pyrotechnic circuits; individual switches to initiate each pyro function; an indication of pyro system readiness; and, an indication of critical pyro circuit failures. Requirements for detection of critical pyro circuit failures are specified in 12.3.1. All pyro switches shall be appropriately guarded.

(4) Subsystem: Electrical Power - D&C shall be provided for interfacing the Orbiter and RMS electrical power subsystems. A readily accessible and appropriately guarded master control switch shall be provided to disable/enable power to the manipulator arms. Actuation of the disable function shall immediately cease arm movement. Normally upon activation/reactivation of the arm, the arm will remain stationary until valid or non-residual manual or automatic commands have been generated.

(5) Subsystem: Lighting - Controls shall be provided for the independent operation of the manipulator arm television viewing light. On/off and variable control shall be provided for RMS integral panel lighting and RMS crew station floodlighting.

(6) Subsystem: Test/Monitor - Provisions shall be made for in-flight testing and monitoring of RMS subsystems. As required for fault correction, the test/monitor design will employ a minimum of additional components. Maximum utilization will be made of existing subsystem capabilities and D&C. Time sharing techniques and general purpose D&C shall be employed to minimize the number of components required.

(7) Caution and Warning (C&W) - The caution and warning section shall be designed to provide the crew with a rapid check of the status of RMS critical subsystem parameters. The design of the caution and warning system shall conform to the requirements of SC-D-0007. Indicator lights shall direct the crew's attention to critical equipment failures or malfunctions which require corrective action. Failures or malfunctions shall be placed in one of two categories as follows:

Warning - Malfunctions of this class affect crew safety and shall require immediate corrective action. There shall be a specific action for each "Warning" indication.

Caution - Each "Caution" indication will denote the occurrence of one of several malfunctions in a given subsystem. Sufficient time must be available for localizing or isolating the fault and performing corrective action. Immediate crew safety is not endangered. Each "Caution" indication directs crew attention to a particular subsystem panel where the appropriate controls and displays will be used as necessary to pinpoint the failure.

A matrix of eight pushbutton switch annunicators and an aural master alarm shall be provided. Any monitored parameter that goes out-of-limits shall trigger both appropriate matrix light and aural alarm. Depressing the lit annunciator shall terminate the aural alarm. The matrix shall stay lit until the condition is corrected.

(a) Caution and Warning Parameters - Parameters and conditions monitored by the Caution and Warning System shall include, but not necessarily limited to; the following:

Tip Velocity - This light would illuminate in the event that the tip velocity was approaching the limit for safe stopping distance. The light would be driven by logic that would be conditioned by the internal mass of the payload, knowledge of the arm position and speed, and other significant parameters.

Collision Avoidance - This light would illuminate in the event that any portion of the arm, or payload being grasped by the arm, comes within a predetermined "safe limit" distance to the Orbiter. The

light would be driven by logic knowledgeable of arm position and any bodies in the manipulator envelope including the arm, payload, and Orbiter surface envelopes.

Critical arm motor failures

Premature release by end effector/handling aids.

Requirements for the collision avoidance system are delineated in 12.4.

(8) Provisions for a Second Arm - When a second RMS arm is utilized, D&C shall be provided to operate the two manipulators in a serial (non-simultaneous) mode. Maximum utilization shall be made of existing subsystem capabilities and D&C, and minimum additional components shall be used. A switch to transfer control between the left and right arms shall be provided. This switch shall be oriented to operate horizontally. D&C for the hold-downs and jettisoning of the second arm shall be provided as specified. A power switch for the second arm and TV light shall also be provided. A TV view selection control for the second arm's camera shall be provided.

12.4 COLLISION AVOIDANCE

The RMS shall incorporate a provision for checking the position of all elements of the manipulator arm and preventing the arm from impacting the Orbiter vehicle. During RMS operations, the collision avoidance system shall be capable of determining the distance between the manipulator and the Orbiter payload bay doors and other Orbiter attached deployable structures. A warning light shall be provided to inform the RMS operator of an impending collision. The operator shall also be made aware of the activation and status of any automatic stop or automatic evasion modes associated with the system. The crew shall be provided with a positive indication when the manipulator arm has been returned to a safe position. The collision avoidance warning light shall be located near the top of the manipulator control panel close to the TV monitor so as to be readily monitored by the operator.

12.5 CLOSED CIRCUIT TELEVISION (CCTV)

The CCTV and CCTV/RMS interface design shall conform to the requirements delineated herein.

12.5.1 Monitors

Two monochromatic CCTV monitors shall be provided for viewing manipulator, docking, and experiment operations. These monitors shall be capable of displaying pictures from any vehicle camera, including the portable color TV camera, payload bay cameras, and payload supplied cameras. Either monitor shall be able to display any camera video. The capability shall exist to simultaneously display video from two sources in split-screen format on the lower monitor. The

design of the monitors shall conform to the general requirements contained within SC-D-0007 and other requirements specified herein. Supplement 1 to SC-D-0007 shall be utilized as a design reference document.

a. Screen Size - The monitor screen size shall be approximately nine inches across the diagonal.

b. Placement - The CCTV monitors shall be located one above the other on the aft bulkhead near the left aft window. The monitors shall be oriented to minimize head and eye movement when changing from out-the-window viewing to monitor viewing during manipulator operations. The monitors shall be located so no more than 55 degrees of combined horizontal head and eye movement is required to view either monitor from the nominal design eye position at the manipulator station. Combined vertical head and eye movement shall be no more than 45 degrees up and 80 degrees down from the nominal eye position. The monitors shall be viewable from all aft flight deck stations and shall not obstruct viewing or reach to the PSS side consoles.

c. Controls - Controls for brightness and contrast shall be located adjacent to each monitor.

12.5.2 TV System Controls

a. TV View Selection - D&C shall be provided to select the camera video outputs to be displayed and provide a rapid visual indication of which camera output is being shown on each monitor. The D&C shall additionally allow the selection of a split-screen video mode, which permits the simultaneous display of video from any two of the onboard cameras to the lower monitor. These functions shall be performed by pushbutton switch-indicators to allow rapid and, if necessary, "blind" selection, and positive annunciation from all aft flight deck stations. The pushbutton signal lights shall illuminate upon pushbutton actuation to indicate which camera or video source has been selected. The switches shall be arranged in a matrix fashion of two horizontal rows with one row for each monitor with each row containing one switch for each camera or video source. The controls shall be located for convenient left hand operations by the RMS operator.

Separate controls shall be provided for interfacing the selected camera or video source with the desired CCTV monitors and other CCTV equipment and modes.

b. Camera Controls - Controls shall be provided to control the following functions for each TV camera:

Pan/Tilt
Zoom
Focus
Iris
Automatic Light Control (ALC)
Gamma Correction

These functions shall be performed by readily accessible controls so as to allow one handed operation without having to look away from the monitors. The pan/tilt, zoom, focus, iris ALC and gamma controls shall be time shared between cameras. Selection of the camera being controlled shall be based upon the camera(s) being displayed on the monitors and controls that select monitors, including the split screen capability of the lower monitor. A means shall be provided to permit rapid realignment of the cameras to their neutral positions.

c. <u>CCTV Power and Miscellaneous Controls</u> - Switches shall be provided to control the power to each camera, each monitor, and other CCTV components such as video switching units as required to minimize power or for operational considerations. Control switches shall also be provided as required for miscellaneous CCTV functions such as systems test, synchronization and system power. Control switches for floodlights associated with a particular camera or cameras shall be located adjacent to the camera controls.

13.0 ORBITER PAYLOAD BAY LIGHTING

13.1 GENERAL

The lighting system shall provide general and specific illumination during the mission to allow the crewmembers to locate, orientate, and manipulate all payloads within the payload bay. The lighting shall provide good visual acuity for rendezvous and docking, payload manipulation into and out of the payload bay, payload movement within the bay and emergency EVA. The lighting source for illumination of the payload bay and payloads may be any type of lamp that is not hazardous to the crew or equipment and is capable of operation throughout the mission timeline.

13.2 ILLUMINATION AREAS

The areas where lighting shall be provided are:

Payload Bay

The TV viewing area

Above the Orbiter to 60 feet.

Payload/manipulator light

Payload/docking light

13.2.1 Payload Bay

Artificial lighting shall be provided to enable the performance of visual tasks either by direct vision or by TV during operations when the sun is blocked by the earth or spacecraft.

These lights shall be capable of providing full illumination during operation in direct sunlight.

a. Lamp - The lamps used for illumination within the payload bay shall be diffused wide-angle flood. The lamps may be either tungsten, mercury discharge, quartz iodine, or any type that will meet the specified illumination requirements.

   If a gas discharge lamp is used, the lamp shall be installed within an environmental sealed fixture.

b. Chromaticity - The color of the light output shall be white with a color temperature not less than 3200° Kelvin.

c. Radiation - The cone of radiation shall not be less than ± 60° (120°) from the perpendicular center of the lamp. The intensity of the light, when measured at 5 degrees increments across the cone, shall not vary more than 10 lumens from one adjacent cone to another.

d. Intensity - The intensity of the lights shall be sufficient to provide a minimum of 10 foot candles throughout the payload bay.

e. Controls - On-off controls shall be provided at the on-orbit station for independent operation of each light.

f. Fixture Mount - Provisions shall be made for independent adjustment of each lamp in the vertical and horizontal direction during ground checkout.

g. Location - To be determined.

h. Number - To be determined.

13.2.2 TV Viewing Light

A light shall be located on the manipulator arm to provide illumination for the television system. The light shall be behind and higher than the TV camera and shall be bore-sighted to intersect the camera line-of-sight at 60 feet.

a. Lamp - The lamps shall be a narrow cone diffused floodlight.

b. Chromaticity - The lamps shall be as specified in 13.2.1.b.

c. Radiation - The cone of radiation shall be $\pm$ 5 degrees greater than the maximum field of view of the TV camera. The intensity across the cone, when measured in 5° increments, shall not vary more than 3 lumens from one adjacent cone to another.

d. Intensity - The intensity of the light shall be sufficient to provide a minimum of 5 foot candles illumination on a payload when the payload is at a distance of 60 feet from the light.

e. Controls - There shall be an on-off switch located on the manipulator station for independent control of this lamp.

f. Fixture - The fixture may be any design that will meet the manipulator requirements.

13.2.3 Payload Manipulator Light

There shall be alight located on the payload bay forward bulkhead to provide full illumination into the payload bay and to provide illumination in the transition area between the payload bay and the overhead (-Z) operation.

a. Lamp - The lamps shall be as specified in 13.2.1.a.

b. Chromaticity - The light color shall be as specified in 13.2.1.b.

c. Radiation - The cone of radiation shall be as specified in 13.2.1.c.

d. Intensity - The intensity of the lamp shall be as specified in 13.2.1.d.

e. Controls - There shall be an on-off switch located at the manipulator station for this lamp.

13.2.4 Payload/Docking Light

There shall be alight located on the top (-Z axis) of the Orbiter between and forward of the two overhead windows to provide illumination for payload manipulation, retrieval, and docking.

a. Lamp - The lamp shall be as specified in 13.2.1.a.

b. Chromaticity - The light color shall be as specified in 13.2.1.b.

c. Radiation - The cone of radiation shall be as specified in 13.2.1.c.

Overlapping Cone - Both the payload/manipulator light and the payload/docking light shall be mounted as to provide at least 20 degrees of overlap of their cones of radiation at a distance between 40 and 50 feet from the top viewing window.

d. Intensity - The intensity of the light shall be as specified in 13.2.2.d.

e. Controls - The controls shall be as specified in 13.2.2.e.

14.0 CLOSED CIRCUIT TELEVISION SYSTEM

14.1 OPERATOR VISUAL INFORMATION REQUIREMENTS

The Shuttle closed circuit television system is required to provide visual information to the RMS operator which will supplement his direct vision and aid in controlling the RMS functions and operations. The operations for which the CCTV is required to generate and display video are docking, payload handling, inflight servicing, satellite capture, spacecraft inspection, and experiment functions. Visual aids such as markings on the payloads, electronic cursors and symbols, and special optical devices may be required to perform these operations.

14.1.1 Docking Operations

When the RMS is used in conjunction with a docking operation, the CCTV shall provide video information to aid the operator in estimating relative position and attitude between the two spacecraft.

14.1.2 Payload Handling

When the RMS is used to deploy or retrieve payloads, the CCTV shall augment the operator's direct vision and aid him in determining that adequate clearances are maintained throughout the operation and that alignment of the objects is adequate for the operation.

14.1.3 Inflight Servicing

When satellites (such as EOS) require inflight servicing, the CCTV shall provide visual data which will assist the operator in aligning and indexing various mechanisms as required. The TV camera mounted on the RMS arm may be used in conjunction with the RMS system to provide a lateral view of an inflight servicing operation. In this case, the RMS/CCTV system must provide stable video data to the operator so that an accurate mechanical indexing may be accomplished.

14.1.4 Satellite Capture

When the RMS system is used to capture a payload, the CCTV system will be used to augment the operator's direct vision. For this operation, the RMS TV camera may have to be located in a position different from that which is required for other operations such as payload handling. Optical and positioning requirements may also be different.

14.1.5 Spacecraft Inspection

The CCTV system may be used in conjunction with the RMS system in inspecting various parts of the Orbiter or other spacecraft which are not within the direct vision of the crewman. Special optical devices and shuttering mechanisms may be required for this task.

14.1.6 Experiment Functions

When the RMS system is used to control, manipulate, or view experiments, the CCTV system shall provide visual information to supplement the operator's direct vision.

14.2 CCTV SYSTEM DESCRIPTION AND PERFORMANCE REQUIREMENTS

The CCTV system will be used to generate and display the video data which is supplementing the RMS operator's direct vision. A baseline system has been defined. However, there are certain specific design characteristics which have not yet been defined. These include optical accuracy requirements and mechanical movement and pointing accuracy requirements. Furthermore, there are additions to the baseline which have been determined to be necessary for the visual feedback to the RMS operator. These clarifications and additions will be discussed in the following sections.

14.2.1 Orbiter CCTV System Baseline

The current baseline for the Orbiter CCTV system consists of four black and white TV cameras with zoom lenses, one portable color TV camera in the cabin, two black and white TV monitors in the cabin aft station, and a video control network. One camera with pan/tilt is located on each of the payload bay bulkheads and on each of the manipulator arms.

14.2.2 Optical Requirements for Bulkhead TV Cameras

a. Angular Field-of-View (FOV) - The angle subtended by the diagonal of the camera field-of-view shall be TBD degrees.

b. Zoom Rates - The lens shall be capable of zooming from one extreme end of the zoom range to the other extreme end in TBD seconds.

c. Optical Tracking Accuracy - The optical center of the image at one extreme end of the zoom range shall not deviate from the optical center at the other extreme end by more than TBD degrees.

d. Optical Distortion Tolerance - The overall distortion produced by the camera lens shall not exceed TBD percent of the image height.

14.2.3 Pan/Tilt Requirements for Bulkhead TV Cameras

a. Angular Boundaries - The pan/tilt mechanism shall be capable of panning the camera + TBD degrees and - TBD degrees from a line parallel to the Orbiter x-axis. The mechanism shall be capable of tilting the camera + TBD degrees and - TBD degrees from a line parallel to the Orbiter x-axis.

b. Pan/Tilt Rates - The pan/tilt mechanism shall be capable of panning the camera from one extreme end of the angular boundary to the other within TBD seconds. The mechanism shall be capable of tilting the camera from one extreme end of the angular boundary to the other within TBD seconds.

c. Positioning Accuracy - The pan/tilt mechanism shall be capable of positioning the camera optical center to within ± TBD degrees of a desired point.

14.2.4 Specific Locations for Bulkhead TV Cameras

The forward bulkhead TV camera should be located at Y_o -95 and Z_o 440. The aft bulkhead TV camera should be located at Y_o 95 and Z_o 440.

14.2.5 Optical Requirements for RMS TV Cameras

a. Angular Field-of-View (FOV) - The angle subtended by the diagonal of the camera field-of-view shall be TBD degrees.

b. Zoom Rates - The lens shall be capable of zooming from one extreme end of the zoom range to the other extreme end in TBD seconds.

c. Optical Tracking Accuracy - The optical center of the image at one extreme end of the zoom range shall not deviate from the optical center at the other extreme end by more than TBD degrees.

d. Optical Distortion Tolerance - The overall distortion produced by the camera lens shall not exceed TBD percent of the image height.

14.2.6 Pan/Tilt Requirements for RMS TV Cameras

a. Angular Boundaries - The pan/tilt mechanism shall be capable of panning the camera + TBD degrees and - TBD degrees from a line parallel to the end effector axis. The mechanism shall be capable of tilting the camera + TBD degrees and - TBD degrees from a line parallel to the end effector axis.

b. Pan/Tilt Rates - The pan/tilt mechanism shall be capable of panning the camera from one extreme end of the angular boundary to the other within TBD seconds. The mechanism shall be capable of tilting the camera from one extreme end of the angular boundary to the other within TBD seconds.

c. Positioning Accuracy - The pan/tilt mechanism shall be capable of positioning the camera optical center to within $\pm$ TBD degrees of a desired point.

14.2.7 Specific Location for RMS TV Camera

The TV camera mounted on the RMS manipulator arm shall be located at the end effector.

14.2.8 Split Screen Requirements for TV Monitors

Each of the TV monitors shall be capable of displaying video from any two of the TV cameras by using a split screen technique.

14.3 CCTV SYSTEM TECHNICAL SPECIFICATION

The detail performance and technical specifications for the CCTV system are described in the document "Statement of Work for the Space Shuttle Closed Circuit Television System" dated February 1975.

15.0 RMS/ORBITER FUNCTIONAL INTERFACES

A typical RMS-to-Orbiter functional interface sketch is shown in Figure 15-1. Electrical power and signal wiring interface will be through the electrical panel feedthrough, located at the forward payload bay bulkhead - station X_O 576. All dedicated displays and controls (D&C) used for RMS operation are located on the port side of the Orbiter flight deck On-Orbit Station. The On-Orbit Station contains D&C for manipulator functions, TV camera control (pan, tilt, zoom, focus), TV monitor switching, payload bay lighting, payload bay door controls, RMS rotation hand controller, translation hand controller, and pyro control. The controls should be arranged and located to provide the proper man-machine interface in a zero-g environment with direct vision capability through the aft facing and overhead windows. Two CCTV monitors and asssociated controls are located in such a manner that the operator can have simultaneous direct and video views of payload/RMS operation in or near the payload bay. The D&C for the primary RMS arm will be modularized and located in the standard 19-inch wide cabinets at the On-Orbit Station. These D&C can be removed and replaced with other payload D&C on those missions not requiring RMS operations. An electrical distribution box is located near the On-Orbit Station and is used for routing wire from connectors located in the payload bay to the RMS display and control equipment modules at the On-Orbit Station.

A second RMS arm can be located on the starboard side on those missions requiring two arm operation. A D&C kit will be provided for operation of the starboard arm, the weight of the arm and D&C kit being chargeable to the payload. Both arms can be operated in a serial manner but not in a simultaneous mode.

A simplified functional interface is shown, the level of redundancy not included, where the dedicated RMS displays and controls are interfaced via hard wires and data bus to the RMS joint motors. It is envisioned that the baselined CRT and keyboard, located at the Mission Station on the starboard side, will be used for loading RMS software programs, initialization, and malfunction routines. However, the primary mode of RMS operation will be by use of dedicated displays and controls.

The manipulator is supported by the Orbiter at four separate locations, as shown in Figure 15-2. The manipulator shoulder will contain both an electrical and structural interface. The remaining three aft deployment/retention systems will contain only a structural interface with the manipulator.

These interfaces will require simplicity, minimal manipulator installation/removal time, and minimal ground support equipment. They should be non-functional inflight, but should use captive parts and be located at points along the longeron where adequate working volume for the physical connections is available.

RMS/ORBITER FUNCTIONAL INTERFACES

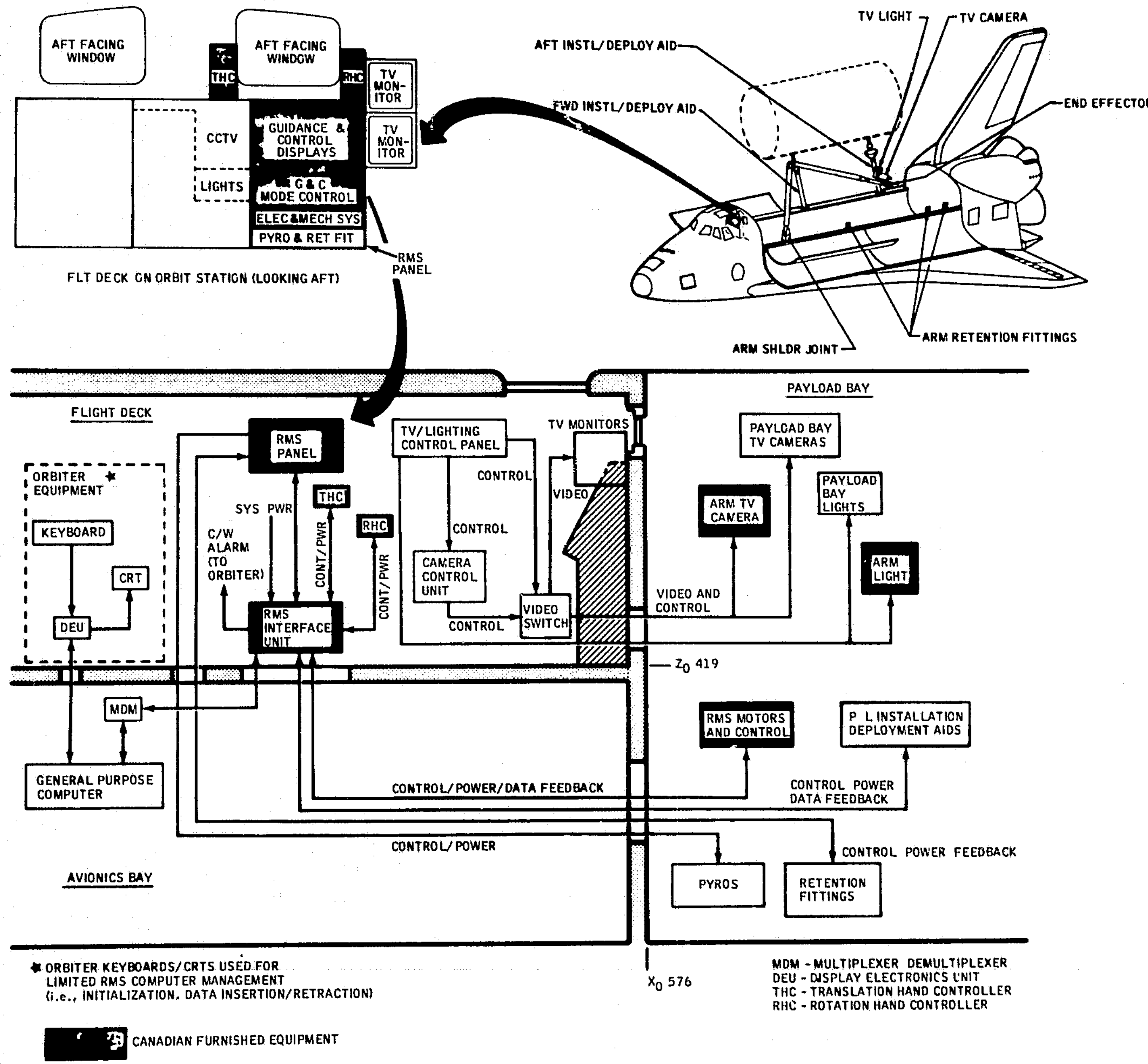


FIGURE 15-1

MANIPULATOR DEPLOYMENT/RETENTION SYSTEM

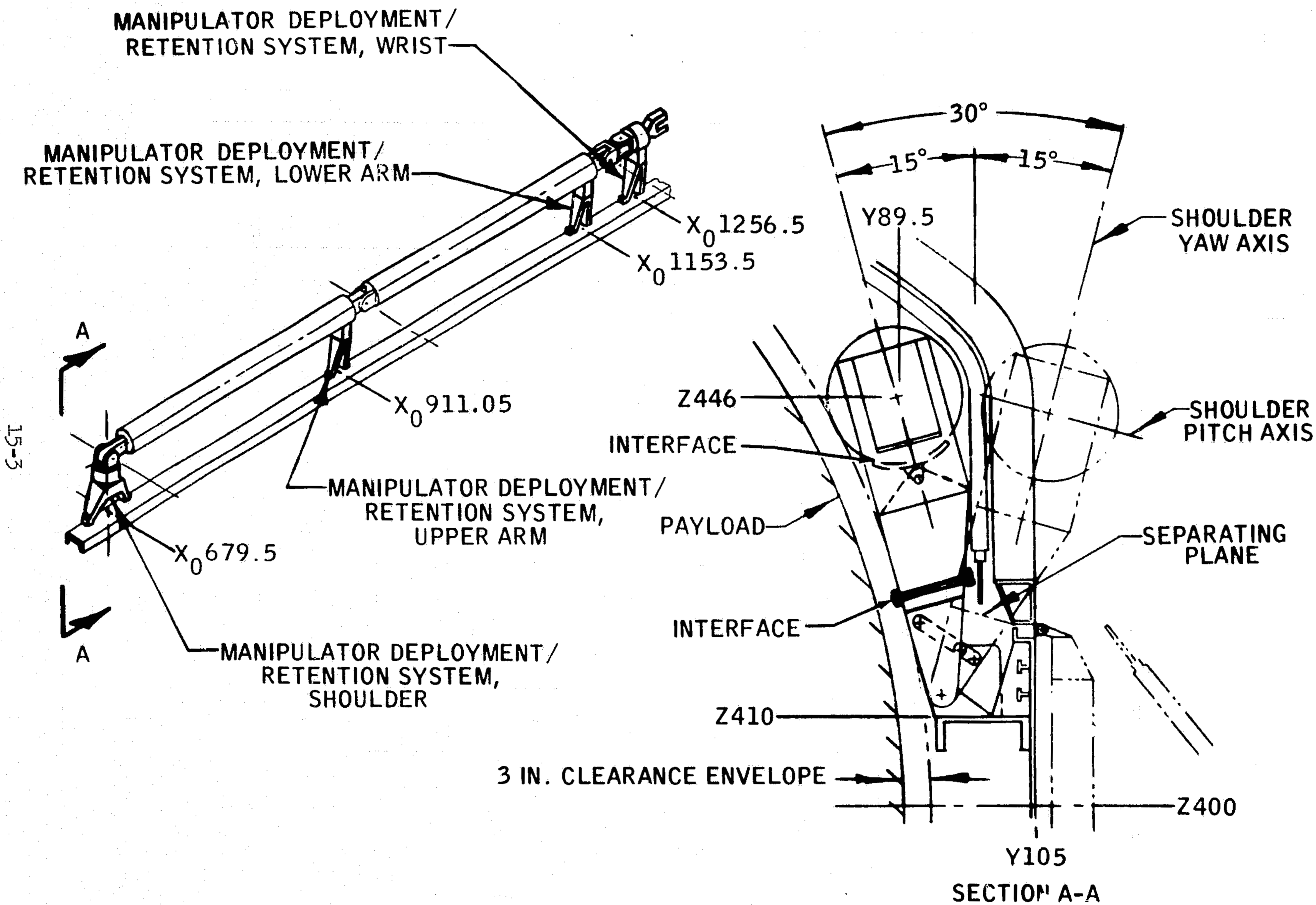


FIGURE 15-2

It is proposed that these interfaces be located as follows: at the manipulator shoulder between the separation plane and the manipulator yaw drive system, and at the three aft deployment/retention systems between the manipulator arm and the retention mechanism.

Figure 15-2 illustrates the present division of development responsibilities for the RMS and the resulting interfaces. The payload bay cameras, video switching assembly, camera control unit and TV monitors will be Government Furnished Equipment.

16.0 OPERATIONAL PROCEDURES

The RMS operation is a complex task composed of five phases: (1) rendezvous with and capture of a freeflying payload, (2) stowing the payload in the payload bay, (3) unstowing a payload from the bay, (4) releasing the payload and separating the Orbiter from it, and (5) performing fine manipulative tasks while the payload is attached to the Orbiter. The operational procedures to accomplish these tasks are primarily payload dependent. They are influenced by such things as the payload mass, its sensitivity to impingement from the Orbiter RCS thrusters (from both contamination and induced disturbance torque), its attitude requirements; and other specific features such as the physical features, appendages (solar panels, antennae, et cetera), attitude control characteristics, and the time available on orbit for performing the operation. There are other factors that must be assumed. For example, it is assumed that there is the necessary redundancy in the RMS control system software to make the system fail operational (degraded)-fail safe, that there is automatic RMS collision avoidance, and that backout maneuvers are permissible to avoid situations that would be hazardous to the Orbiter at the sacrifice of the RMS if necessary. Many of the payloads identified to date that require deployment or retrieval by the RMS have stabilization systems that are not adequate to allow the RMS related operations to be performed in a normal manner. Operational techniques will have to be developed to accomplish these operations, particularly in the areas of approach to capture and the separation of the Orbiter from the payload. In some instances, the time available for deployment or retrieval operations is very limited. The 3A and 3B reference missions are examples of this situation (Tables 16-I and 16-II). Here again, operational techniques and hardware design must be developed to accomplish the task at hand.

There are several different support devices that are not a part of the RMS itself, but will have to be developed to allow the basic RMS to do its job of retrieving payloads. For example, to perform the maneuvers required to minimize the contamination and overpressure effects on freeflyers during the final approach leading up to capture, the crew must have range and range-rate information down to 50 feet and 0.1 fps. This information will probably be supplied by some ranging device which may be added to the Orbiter or by modifications to the existing Orbiter radar. In addition to the range and range rate information, the crew will need some sort of aiming device that will aid in aligning the Orbiter for its final translation maneuver to the target.

There are a variety of operations that the RMS may be asked to perform in addition to deployment and retrieval. The extent of these "other" tasks is dependent on the final configuration and capabilities of the RMS. The RMS may be asked to support the Orbiter by locating lights and cameras for inspection of various parts of the vehicle and to assist in its repair if required. It will aid in EVA operations by serving as a transportation path to worksites with the addition of handrails which are installed before launch. It will also be useful for providing a portable workstation at the EVA site and can be used to handle large or bulky equipment for the EVA crewmen.

TABLE 16-I

RMS TIMELINE MISSION 3A

	G.E.T. START	FINISH
OPEN PAYLOAD BAY DOORS	-	14:34
DEPLOY AND CHECK OUT RMS	14:54	19:54
RELEASE PAYLOAD RETENTION MECHANISM	19:54	-
ROTATE PAYLOAD CLEAR OF PAYLOAD BAY (PIDA)	-	-
GRAPPLE PAYLOAD (RMS)	-	-
DISCONNECT PIDA	-	-
MOVE PAYLOAD TO DEPLOYMENT POSITION (RMS)	-	-
RELEASE PAYLOAD AND MOVE RMS CLEAR	-	27:43
INITIATE RCS SEPARATION MANEUVER TO STATION-KEEPING POSITION	27:43	-
RETRACT HANDLING AIDS	28:00	29:00
STOW RMS	29:00	31:00
CLOSE PAYLOAD BAY DOORS	46:42	-

NOTE: UNDERLINED TIME FROM MPAD REFERENCE MISSION TIMELINE

TABLE 16-II

RMS TIMELINE
MISSION 3B

	G.E.T. START	G.E.T. FINISH
OPEN PAYLOAD BAY DOORS	-	14:34
DEPLOY AND CHECK OUT RMS	29:00	34:00
DEPLOY PIDA	34:00	35:00
ORBITER COMPLETES RENDEZVOUS AND STATION KEEPS 100 FT FROM PAYLOAD	35:00	38:30
ORBITER MOVES TO CAPTURE POSITION AND ATTITUDE	38:30	40:30
CAPTURE PAYLOAD AND DAMP RELATIVE RATES (RMS)	40:30	-
ENGAGE PIDA	-	-
DISENGAGE RMS FROM PAYLOAD AND MOVE CLEAR	-	-
ROTATE PAYLOAD INTO PAYLOAD BAY (PIDA)	-	-
SECURE PAYLOAD RETENTION MECHANISM	-	-
STOW RMS	-	48:40
CLOSE PAYLOAD BAY DOORS	48:40	-

NOTE: UNDERLINED TIMES FROM MPAD REFERENCE MISSION TIMELINE

The RMS may also be used to aid in crew rescue operations. The manipulator will be able to aid in payload operations by removing launch protective covers, deploying antennas or solar panels, locating TV cameras for inspection purposes and changing replaceable modules. In some instances, the RMS may even position sensors for data taking. If RMS support is required with a Spacelab manned module in the payload bay, the manipulator may be controlled from a portable station at the aft end of the Spacelab where an unobstructed view of the remainder of the payload bay is available. All of this is conceptual, but it represents real tasks that the RMS may be asked to perform when it becomes operational.

17.0 RMS SIMULATIONS AND CREW TRAINING

A variety of simulation devices will be required to support the development of an RMS, the integrated procedures required to operate it, and to train the flight crewmembers to perform the operations utilizing the RMS. For example, simulations will have to be employed before an acceptable RMS control system can be identified. The control systems under consideration must be optimized and then compared under simulated flight conditions which include such things as vehicle/payload dynamics, field of view (both CCTV and out of the windows), and lighting.

After the RMS design is frozen and the operational techniques are developed, the crew training will begin. This training will be conducted in two phases. The first phase, basic RMS training, will be given to all the potential RMS operators. It will include about 4 hours of classroom instruction, and about 24 hours using the RMS training facility. The second phase of crew training will begin when the crews are selected for a specific flight. The amount of RMS training spent here will be a direct function of the RMS tasks to be performed on the specific flight. The RMS crew training objectives will be:

a. To exercise each phase of the RMS operations in a part task mode.

b. To exercise the end-to-end RMS operation inclusive of all phases.

c. To exercise all malfunction modes.

d. To exercise all handling procedures requiring fine manipulation.

In order to accomplish this training, the RMS training facilities must be capable of providing simulation of:

a. An end-to-end RMS/Orbiter training task capability.

b. All time critical functions involved in the training tasks.

c. All RMS, Orbiter and payload dynamics

d. All handling and fine manipulative procedures

e. All RMS malfunctions

The RMS task is totally dependent upon the operator being able to observe the RMS operation. RMS operation will require the full complement of visual aids available to the Orbiter aft crew station; overhead and aft windows and RMS mounted TV (CCTV) system. Both overhead and aft windows and RMS mounted TV camera will be used for the rendezvous and capture phase and the release phase. The aft windows and the entire CCTV system will be used for the remaining phases which involve the payload bay and installation aids; stowing, unstowing, and fine manipulative tasks.

18.0 CONTROL WEIGHTS

The RMS control weights shall not exceed the weights shown on Table 18-I.

The control weights include all the items located in the cargo bay and crew cabin of the Orbiter required to operate the baseline RMS. The following functional items are included in the control weights.

a. Manipulator Arm - upper and lower arm, joints, end effector, internal wiring, handholds, et cetera.

b. Manipulator Deploy and Retention - arm retention mechanism, deploy mechanism.

c. Manipulator Support and Installation - arm support and installation hardware.

d. Electrical Installation - arm light, cargo bay wiring installation, and crew cabin wiring installation.

e. Avionics Installation - arm mounted T.V. camera (black and white), cabin hand controller, manipulator interface unit, manipulator MDM, and manipulator control panel.

f. Payload Installation and Deployment Aid - two arms.

g. Margin - weight allowance for deficiencies in estimated or calculated values, design changes due to manufacturing and development problems, more severe design requirements and other in-scope causes that are not identifiable at this time.

The optional second manipulator arm is payload chargeable and the weight shall not exceed the weight shown on Table 18-I.

TABLE 18-I

RECOMMENDED CONTROL WEIGHT

FUNCTIONAL ITEMS	CONCEPT BASELINE	2ND ARM
MANIPULATOR ARM	540	540
MANIPULATOR DEPLOY AND RETENTION	247	247
MANIPULATOR SUPPORT AND INSTALLATION	73	73
ELECTRICAL INSTALLATION	26	14
AVIONICS INSTALLATION	71	27
PAYLOAD INSTALLATION AND DEPLOYMENT AID	250	N.A.
MARGIN	66	66
TOTAL	1273	967